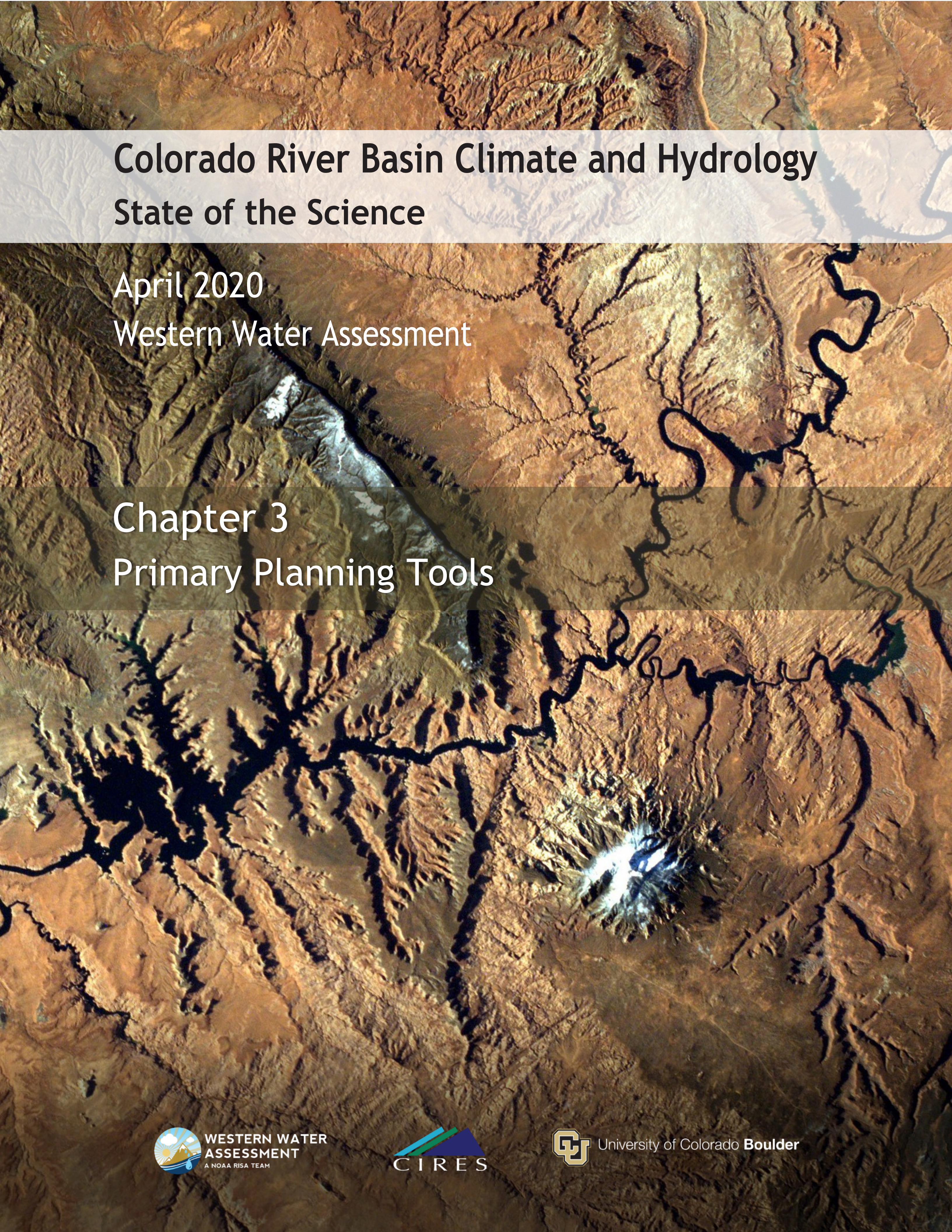

Colorado River Basin Climate and Hydrology

State of the Science

April 2020

Western Water Assessment

Chapter 3

Primary Planning Tools

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

CIRES

University of Colorado Boulder

Colorado River Basin Climate and Hydrology
State of the Science

April 2020

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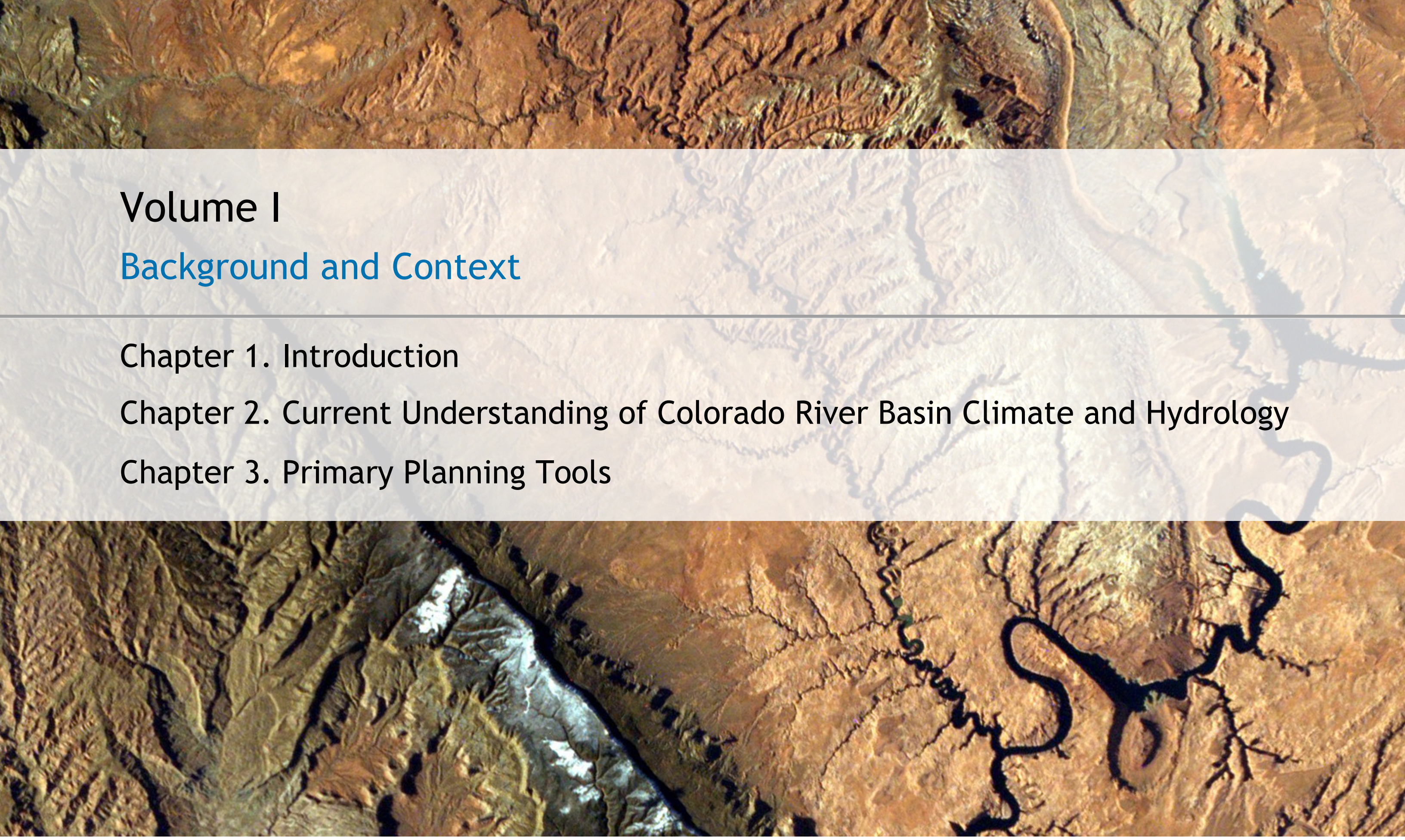

Volume I

Background and Context

Chapter 1. Introduction

Chapter 2. Current Understanding of Colorado River Basin Climate and Hydrology

Chapter 3. Primary Planning Tools

Volume I of the Colorado River Basin State of the Science report provides important background and context for considering the different datasets, models, and tools described in the subsequent volumes and chapters. Chapter 1 succinctly lays out the need for the report as well as its objectives, intended audience, approach, and organization. It also contains a primer on sources of uncertainty to help readers navigate more focused discussions of uncertainty in later chapters.

Chapter 2 is a technical report unto itself; it describes what is known about the fundamental features of the Colorado River Basin's hydroclimate, their spatial and temporal variability, and the mechanisms behind that variability. This knowledge base is dependent on the primary datasets and models described in Volume II (Chapters 4, 5, and 6) while also informing the productive application of those data and models, and similarly it underpins the application of the weather, climate, and streamflow forecasting methods described in Volume III (Chapters 7 & 8). The chapter concludes with a detailed discussion of recent trends in basin hydroclimate and their likely causes, which provides critical context for the long-term planning datasets described in Volume IV (Chapters 9–11).

Chapter 3 provides a detailed overview of the three primary Reclamation operations and planning models that support basin decision making. It describes the underlying configurations, assumptions, and applications of the three models. The chapter details how these models use observational data, streamflow forecasts, and planning hydrologies as a prelude to the discussion of those inputs in subsequent chapters.

Chapter 3

Primary Planning Tools

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Key points

- Three monthly Reclamation models, developed in RiverWare™, support planning at three time scales: short-term (up to 24 months), mid-term (up to 60 months), and long-term (multiple decades).
- The models use rules to incorporate operational policies set forth in Records of Decisions and other operational agreements, and some long-term studies also explore potential alternative policies.
- Hydrologic inputs to the short-term and mid-term models are either flows forecast by the NOAA Colorado Basin River Forecast Center (CBRFC) or statistical averages of observed flows.
- Hydrologic inputs to the long-term model may be based on historical hydrology, paleohydrology, climate change-informed hydrology, or hybrids.
- Measured Upper Basin water demands for the short-term and mid-term models are accounted for in the CBRFC's forecast; Lower Basin water demands are provided by Lower Basin water users and Mexico. Both Upper and Lower Basin demands for the long-term model are based on projections supplied by water users.
- Uncertainties, errors, and limitations arise from input data sources, assumptions about the future, and necessary simplifications of a complex water supply system.

3.1 Introduction

Planning and operations models support decision making by providing computer-based representations of water supply systems that allow analysis of a variety of hydrologic, operational, administrative, and infrastructure scenarios. They are designed to represent systems with networks of inflows, uses, and storage that serve multiple objectives, and they are built to generate or accept large databases of streamflow data. These models track the movement and storage of water through river reaches, reservoirs, canals, and other infrastructure, and account for withdrawals and gains and losses. They usually simulate operations and the administrative rules that govern water allocation.

World-wide, a number of generalized modeling tools have been used to simulate large scale river basin systems. There are differences and similarities among the tools in core solver type and the kinds of processes simulated, but most of them are flexible as to time step, spatial extent, resolution, and operations. They have advantages and limitations that make them more or less suitable for particular analyses. For more information about generalized, river basin system modeling tools, and some in-depth comparisons, see Wurbs (1994; 2012); Stratus Consulting (2005); Zagona (2010); US Army Corps of Engineers (2012); Johnson (2014); California Dept.

of Water Resources (2016; 2019); Colorado State University (2017); DHI (2019); Lynker (2019); SEI (2019); Texas A&M University (2019a; 2019b).

3.2 Reclamation's models

Reclamation manages the system reservoirs on the Colorado River within the legal and political framework captured in a body of documents known as "the Law of the River" (Nathanson 1978; Reclamation 2007e; 2015b). The Law of the River specifies Colorado River entitlements and priorities and comprises numerous operating criteria, regulations, and administrative decisions included in federal and state statutes, interstate compacts, court decisions and decrees, an international treaty, and contracts with the Secretary of Interior. As such, modeling undertaken by Reclamation to support basin management must be able to represent both the challenging institutional setting and the complex physical system. The results of modeling studies are a familiar, standardized foundation for Reclamation's stakeholder outreach and in some instances are the basis for determining official operations. The core of this modeling is a mass balance calculation that accounts for water entering the system, water leaving the system (e.g., from consumptive use of water, trans-basin diversions, evaporation), and water moving through the system (i.e., either stored in reservoirs or flowing in river reaches).

Since the 1990s, Reclamation has developed system models using RiverWare™, an object-oriented, generalized river basin modeling platform developed in partnership with the University of Colorado's Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) and the Tennessee Valley Authority (Biddle 2001; Zagona et al. 2001).

Reclamation's three basin-wide planning and operations models are the 24 Month Study (24MS), the Mid-Term Probabilistic Operations Model (MTOM), and the Colorado River Simulation System (CRSS). The three models and their applications are summarized in Figure 3.1.

RiverWare Operations Model	Time Horizon	Primary Use
24-Month Study Model (24MS)	1-2 years	Annual Operating Plan tier determinations and projections of current conditions
Mid-term Probabilistic Operations Model (MTOM)	1-5 years	Risk-based operational planning and analysis
Colorado River Simulation System (CRSS)	Decades	Long-term planning studies, criteria development, and risk analysis

Figure 3.1

Reclamation's basin-wide planning and operations models (Source: adapted from Fulp 2003)

The core elements that characterize the three models are listed below.

- Purpose
- Time step and simulation horizon
- Structure and resolution
- Physical processes (evaporation and bank storage)
- Inputs
    - Initial reservoir conditions
    - Operational policies
    - Future water use/demand
    - Future inflows
- Outputs (variables, deterministic vs. probabilistic)

All three models run on a monthly time step, use the same methods to estimate reservoir evaporation and bank storage (monthly coefficients applied to surface area and single coefficients applied to total reservoir storage, respectively), and represent the same operating policies, but are otherwise different in multiple respects.

RiverWare supports "rule-based" simulation (Zagona 2010), in which logic statements, rather than hard-coded values, are used to represent operational policy. This capability makes RiverWare well suited to simulate the requirements stipulated by the Law of the River. A simple rule might take the form of "If Reservoir A elevation is x, and forecast inflow is y, then make release z." An example of a RiverWare rule that might be executed in a Colorado River simulation is provided in Figure 3.2.

The “objects” in RiverWare’s object-oriented modeling system may be reservoirs, river reaches, stream confluences, diversions, inflows, canals, pipelines, gages, or other water resources features (CADSWES 2018). Each object is assigned attributes ranging from its capacity to its representation of physical processes. Water flows between objects via links, but mass balance is calculated at the object level.

Each model is described in detail in the sections that follow, organized from shortest to longest time scale.

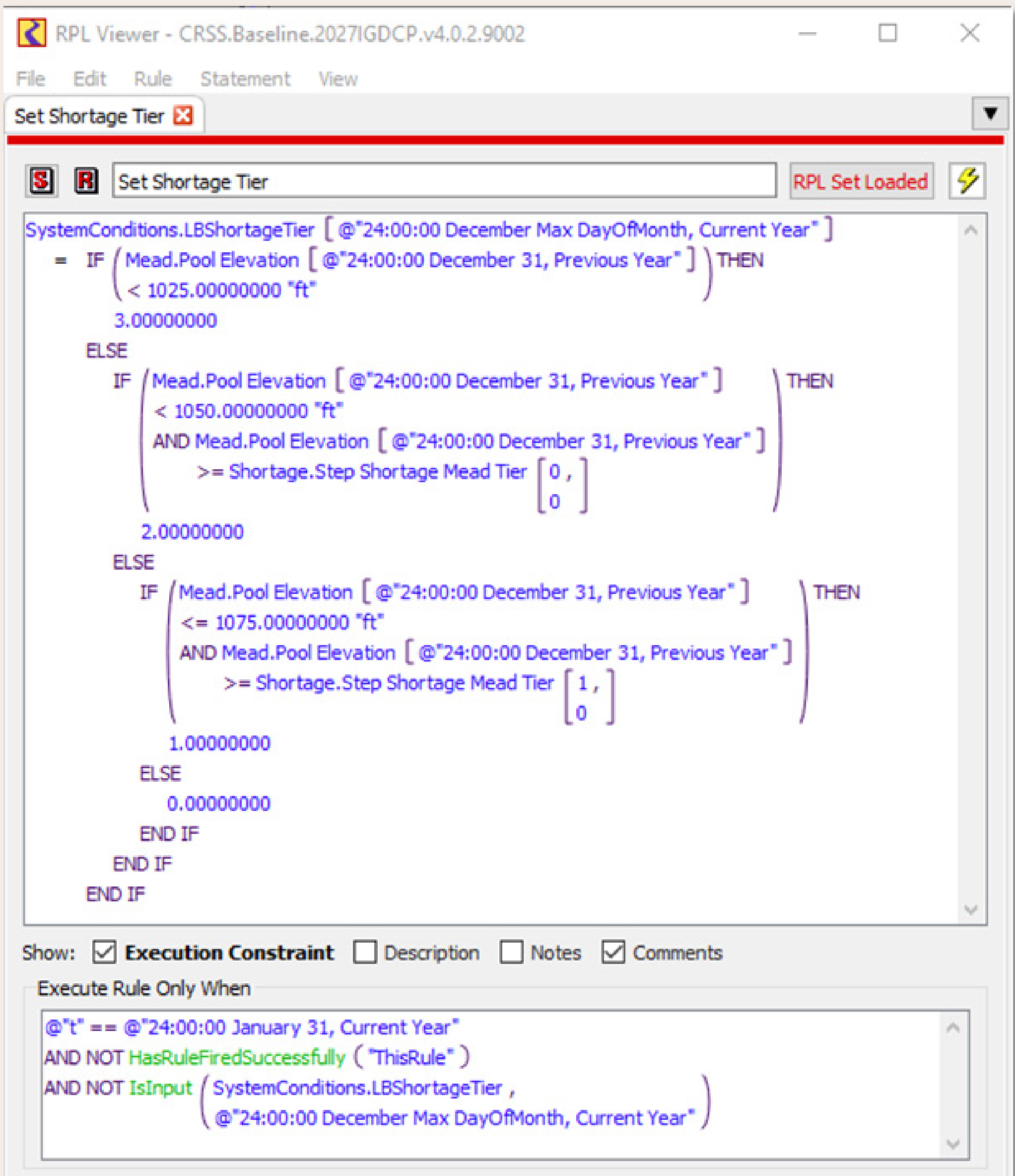

Figure 3.2

Sample rule from CRSS as implemented in RiverWare (Source: Reclamation)

24-Month Study Model (24MS)

The 24-Month Study model (24MS) is an operations model developed by Reclamation to support planning for the upcoming 24 months. 24MS began as a FORTRAN program, was re-implemented in RiverWare in 1997, and continues to be refined to better represent the physical system and evolving operational policies.

The model is run every month to provide basin-wide operational updates as hydrology and demand projections evolve. The August modeling results are used to determine the annual operating conditions for Lake Powell and Lake Mead for the upcoming year as reported in Reclamation's Annual Operating Plan for Colorado River Reservoirs (AOP). Under certain conditions, the April modeling results may prompt adjustments to Powell operations. The operating tiers for Lake Powell and Lake Mead determine release volumes from Lake Powell, and also whether and by how much deliveries from Lake Mead to Lower Basin water users and Mexico will be reduced (under shortage conditions) or supplemented (under surplus conditions). Operational tiers, release volumes, and water delivery conditions were set forth in the 2007 Interim Guidelines (U.S. Secretary of the Interior 2007) and Minute 319 (International Boundary and Water Commission 2012), and were more recently augmented and extended by the Drought Contingency Plan (DCP; Reclamation 2019c) and Minute 323 (International Boundary and Water Commission 2017). Per the Interim Guidelines, the August 24MS projections of January 1 reservoir elevations determine the operating tiers for Lakes Powell and Mead for the upcoming calendar year. Subsequent April 24MS projections of September 30 elevations of Lakes Powell and Mead may result in an adjustment to the annual release volume from Lake Powell.

The structure of 24MS is driven by its core purpose, which is to simulate operations at 12 Reclamation reservoirs. Each 24MS simulation is initialized with current reservoir elevations (conditions from the last day of the previous month). Every time 24MS is run, Reclamation employees in the Upper and Lower Colorado regional reservoir operations offices input projected reservoir operations by hand. This manual approach takes advantage of the expertise of reservoir operators and obviates the need for reservoir operations logic in the model but limits the ability to incorporate operational and hydrologic uncertainty (discussed below and in Reclamation 2015a). The model is not exclusively manual input—in years 2 and 3 of the 24MS simulation, Lower Basin operations are automated and driven by rules that reflect projected operating conditions for Lake Mead.

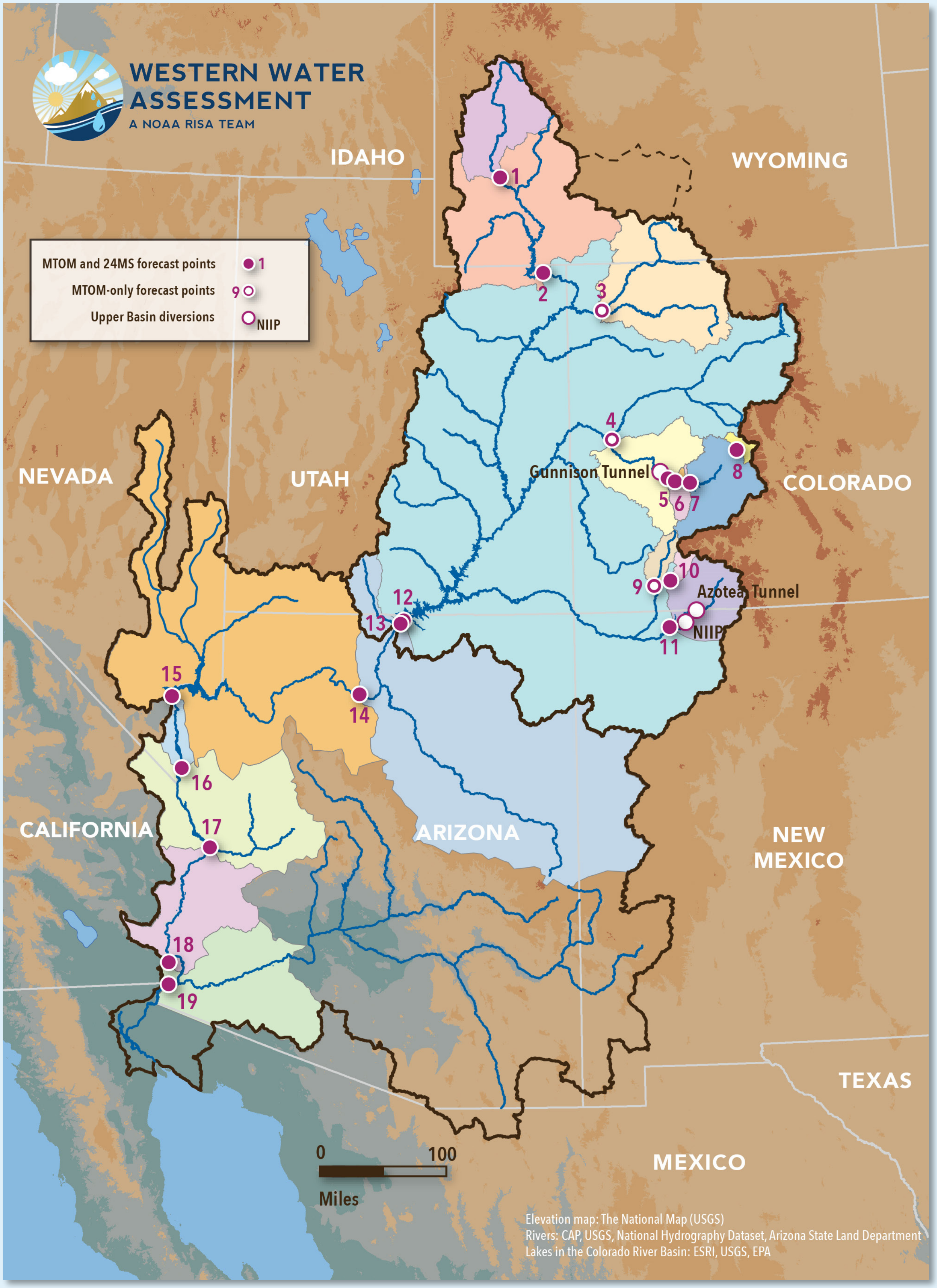

Figure 3.3

Map of sub-basins and forecast points for 24MS and MTOM. The basins in the map are color-coded to match the sub-basins shown in Table 3.1. (Source: Reclamation)

Table 3.1

Sources of inflows used in 24MS and MTOM. The cells in the table are color-coded to match the sub-basins shown in Figure 3.3. (See additional explanation below; Source: Reclamation)

CRSS natural flow point	USGS Gage Name	USGS Gage #	Relevant 24MS/MTOM forecast sub-basin	Relevant MTOM/24MS forecast point
1	Colorado River At Glenwood Springs, CO	09072500	Lake Powell	12
2	Colorado River Near Cameo, CO	09095500		
3	Taylor River Below Taylor Park, CO	09109000	Taylor Park Reservoir	8
4	Gunnison River Below Blue Mesa, CO	09124700	Blue Mesa Reservoir	7
5	Gunnison River At Crystal , CO	09128000	Crystal Reservoir	5
			Morrow Point Reservoir	6
6	Gunnison River Near Grand Junction, CO	09152500	Gunnison R. gains Crystal to Grand Junction*	4*
7	Dolores River Near Cisco, UT	09180000	Lake Powell	12
8	Colorado River Near Cisco, UT	09180500		
9	Green R Bel Fontenelle Res, WY	09211200	Fontenelle Reservoir	1
10	Green R. Nr Green River, WY	09217000	Flaming Gorge Reservoir	2
11	Green River Near Greendale, UT	09234500		
12	Yampa River Near Maybell, CO	09251000	Yampa River at Deerlodge Park*	3*
13	Little Snake River Near Lily, CO	09260000		
14	Duchesne River Near Randlett, UT	09302000	Lake Powell	12
15	White River Near Watson, UT	09306500		
16	Green River At Green River, UT	09315000		

CRSS natural flow point	USGS Gage Name	USGS Gage #	Relevant 24MS/MTOM forecast sub-basin	Relevant MTOM/24MS forecast point
17	San Rafael River Near Green River, UT	09328500		
18	San Juan River Near Archuleta, NM	09355500	Vallecito Reservoir	10
			Navajo Reservoir	11
19	San Juan River Near Bluff, UT	09379500	Animas R. at Durango*	9*
			Lake Powell	12
20	Colorado R At Lees Ferry, AZ	09380000	Lake Powell	12
			Gains Powell to Lees Ferry Gage (not visible on map)	13
21	Paria River at Lees Ferry, AZ	09382000	Gains above Grand Canyon	14
22	Little Colorado River near Cameron, AZ	09402000		
23	Colorado River near Grand Canyon, AZ	09402500		
24	Virgin River at Littlefield, AZ	09415000	Gains above Hoover (Lake Mead)	15
25	Colorado River below Hoover Dam, AZ-NV	09421500		
26	Colorado River below Davis Dam, AZ-NV	09423000	Gains above Davis (Lake Mohave)	16
27	Bill Williams below Alamo Dam, AZ	09426000	Gains above Parker (Lake Havasu)	17
28	Colorado River below Parker Dam, AZ-CA	09427520		
29	Colorado River above Imperial Dam, AZ	09429490	Gains Parker to Imperial	18
NA	(CRSS only extends to Imperial)	--	Gains Imperial to Northerly International Border	19

Table 3.1 summarizes how water is aggregated in CRSS via natural flow points versus how it is aggregated in 24MS and MTOM via forecast points. The colors in the two right-most columns correspond to the colors of the MTOM/24MS sub-basins in Figure 3.1. In general, the table conveys spatial relationships and does not imply that natural flows are used directly to derive 24MS/MTOM forecasts (which are generated by the CBRFC). Forecast sub-basins/points with an asterisk (*) only exist in MTOM; the RiverWare rules used by MTOM need these sub-basins to approximate how

the reservoir operators use gage information when running the 24MS manually.

Inflows

Streamflow "forecasts" used in 24MS runs are actually flow sequences constructed by piecing together flows from some or all of the sources listed in Table 3.1.

ESP flow sequences are created by initializing the CBRFC models with current basin conditions (e.g., soil moisture, antecedent streamflow, snowpack). Then, historical 1981 to 2015 temperature and precipitation data are used to drive the CBRFC streamflow forecast modeling workflow, generating 35 equally likely 60-month forecasts from those initial conditions (Powell 2015). "Official" CBRFC forecasts combine near-term temperature and precipitation forecasts, ESP modeling, and expert forecaster analysis, the latter of which sometimes refines the forecast based on anticipated upcoming storms. The ESP and official forecasting procedures used by the CBRFC are described in more detail in Chapter 8.

24MS is run every month to generate "most probable" projections of reservoir levels. The inflow sequences used in these runs are constructed differently depending on the month. Figure 3.4 shows how construction of the Upper Basin most probable deterministic flow sequence varies over the course of a water year. To aid understanding of Figure 3.4, the October, January, and June sequences are described below.

In October, median flow values for the first three months are taken from the official forecasts provided by the CBRFC; for the rest of Year 1 (always defined as the span from the current month through the upcoming September), the monthly running median of the ESP forecast is used; Year 2 (always defined as the span from the upcoming October through following September) uses 30-year climatology *except* for October and November where a linear interpolation between the median ESP forecast value for September and climatology for January is used to smooth the sequence. This method uses actual forecasted values in the first three months only, it does not use or reflect actual forecasted values in the other months.

For January runs of the 24MS most probable run, flows for the first three months are again taken from median CBRFC official forecasts. April through July flow values are the median monthly values from the CBRFC's April-through-July runoff forecasts. Starting with the August flow value, the flow sequences then revert to the same procedure used for the October flow sequences: median ESP through September followed by interpolation to climatology in Year 2 and beyond.

For the June most probable 24MS run, the first three months' flows are median CBRFC official forecasts followed by median ESP values for September through Year 2.

	Year 1												Year 2											
Month Issued	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Oct	RFC	RFC	RFC	ESP Oct	ESP Oct	ESP Oct	ESP Oct	ESP Oct	ESP Oct	ESP Oct	ESP Oct	ESP Oct	inter-polate	inter-polate	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg
Nov		RFC	RFC	RFC	ESP Nov	ESP Nov	ESP Nov	ESP Nov	ESP Nov	ESP Nov	ESP Nov	ESP Nov	inter-polate	inter-polate	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg
Dec			RFC	RFC	RFC	ESP Dec	ESP Dec	ESP Dec	ESP Dec	ESP Dec	ESP Dec	ESP Dec	inter-polate	inter-polate	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg
Jan				RFC	RFC	RFC	Official A-J	Official A-J	Official A-J	Official A-J	ESP Jan	ESP Jan	inter-polate	inter-polate	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg
Feb					RFC	RFC	RFC	Official A-J	Official A-J	Official A-J	ESP Feb	ESP Feb	inter-polate	inter-polate	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg
Mar						RFC	RFC	RFC	Official A-J	Official A-J	ESP Mar	ESP Mar	inter-polate	inter-polate	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg
Apr							RFC	RFC	RFC	Official A-J	ESP Apr	ESP Apr	inter-polate	inter-polate	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg
May								RFC	RFC	RFC	ESP May	ESP May	inter-polate	inter-polate	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg	30-yr Avg
Jun									RFC	RFC	RFC	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun	ESP Jun
Jul										RFC	RFC	RFC	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul	ESP Jul
Aug											RFC	RFC	RFC	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug	ESP Aug
Sep												RFC	RFC	RFC	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep	ESP Sep

RFC values are issued by the Colorado Basin River Forecast Center (RFC) as the official forecast values for the next three-month period of time. The values are calculated using Ensemble Streamflow Predictions (ESP) modeling and/or Statistical Water Supply (SWS) modeling.

Official A-J values are official forecast values issued by the RFC for the April-July runoff period using SWS and ESP. Apr-Jul water supply forecast volume is disaggregated by the RFC.

30-yr Avg values are the monthly average inflow values from the most recent 30 water years which is rolled forward every 10 years on the XXX1 year of each decade. For example, the 30-year average for 2014 would be 1981-2010. This data is calculated using a database maintained by the Bureau of Reclamation Upper Colorado Region (UCBOR). A water year begins October 1 and ends September 30.

Interpolated values are calculated by UCBOR and are based on percent of the 81-10 average. The method takes the percent of average of the previous month's forecast value and interpolates over two months to the percent of average for the month following the interpolation period. This is done to smoothly transition between the end of the current water year and the next water year.

ESP monthly values are generated using the RFC ESP forecasted volume for the water year using the current month's initial hydrological conditions. The RFC provides monthly volumes consistent with the 3-month forecast and the water year ESP volume.

Figure 3.4

24MS Most Probable Forecast construction methods for Upper Colorado unregulated inflows. (Source: Reclamation)

Lower Basin flow sequences for the most probable 24MS run are based on historical intervening flows. These are flows that have been calculated using mass balance between upstream and downstream gages. For each Lower Basin inflow, a trace is constructed by stringing together each month's 5-year average flow from the preceding five years. For example, the May inflow used in this run would be the average of the previous five May intervening flows and the June inflow would be the average of the previous five June intervening flows, etc. This is true for Years 1 and 2 and beyond.

In January, April, August, and October, two additional 24MS simulations are performed to characterize the uncertainty associated with the forecast; these are the "maximum probable" and "minimum probable." The flow sequences for these runs use the same data sources but in most places use percentiles instead of averages. For the Upper Basin, the maximum probable traces are constructed using the 90th percentile of the CBRFC's official forecasts, April-through-July forecasts, and ESP forecasts in Year 1, then linear interpolation is used to match up with the 75th percentiles of monthly values from the 1981–2010 record. Year 3 (when modeled) reverts back to the 30-year average. The minimum probable traces are constructed the same way as the maximum probable traces except that they start with 10th percentile flows in Year 1, go to 25th percentile flows in Year 2, and then revert back to 30-year average flows. The percentiles used for maximum and minimum traces step back toward the mean because it is assumed that multiple years of extreme conditions in a row will not occur.

In January, April, and October, the maximum probable Lower Basin flows are constructed by stringing together flows corresponding to the 90th and 75th percentiles of the monthly flows from the preceding five years for Years 1 and 2, respectively, then reverting back to the average for Year 3 (i.e., the procedure for the most probable traces is used in Year 3). In a similar fashion, the 10th and 25th percentile flows are used to construct the flow sequence for the minimum probable trace. For August runs, the months of August and September use 5-year averages even for the maximum and minimum probable, and then Years 2 and 3 use 90th and 75th or 10th and 25th percentiles, respectively. Only the runs using the most probable flows are used for setting operational tiers.

Demands

Reclamation does not explicitly model Upper Basin water use in 24MS, but the unregulated inflow forecasts provided by the CBRFC have the impacts of some upstream uses in them (any "unmeasured" depletions and return flows are still represented in the inflows; the CBRFC's unregulated streamflow development is discussed in more detail in Chapters 5 and 8). There are three exceptions: the 24MS model's projections of monthly diversions from the Gunnison Tunnel, the Azotea Tunnel, and the Navajo Indian Irrigation Project (NIIP); the unregulated inflows provided by the CBRFC have not been depleted by those diversions. Lower Basin demands are modeled based on monthly schedules provided by water users. Water users provide updated schedules throughout the year.

Output

Output from 24MS consists primarily of monthly projected reservoir elevations, releases, and power generation. These results are posted in tabular form to the Reclamation website each month and provide decision support for basin stakeholders. Example 24MS output showing projected elevations in Lakes Powell and Mead from January, 2020 runs are provided in Figure 3.5 and Figure 3.6, respectively.

24MS output

Look for links under the heading "2-Year Projected Operations" at https://www.usbr.gov/lc/riverops.html for monthly tabulated 24MS output.

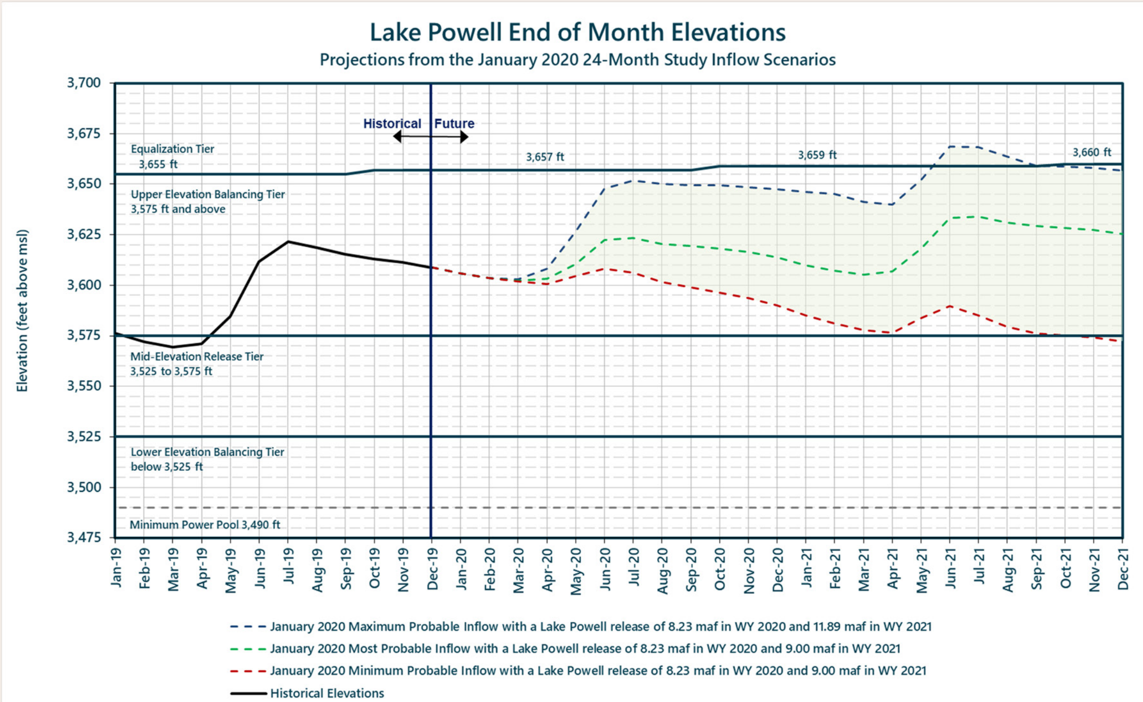

Figure 3.5

Example 24MS output for Lake Powell. (Source: Reclamation)

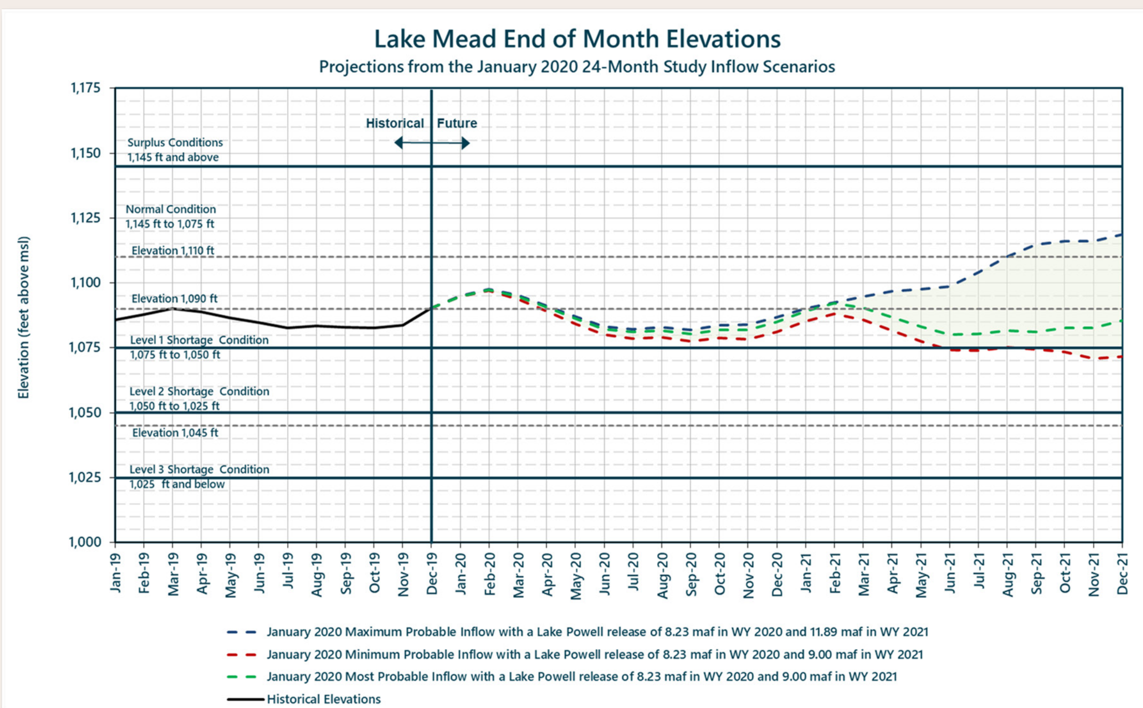

Figure 3.6

Example 24MS output for Lake Mead. (Source: Reclamation)

Mid-Term Probabilistic Operations Model (MTOM)

MTOM was developed in 2015 to enable Reclamation to simulate reservoir operations under a wider range of potential future streamflow than is used in 24MS (Bracken 2011; Reclamation 2015). The 24MS model is limited in its ability to incorporate hydrologic and operational uncertainty because it is a deterministic model that uses a single hydrologic trace and reservoir operations must be input manually. MTOM addresses this by using an ensemble of hydrologic traces and rules that execute reservoir operations throughout the basin in accordance with the Law of the River. The rules and their relationships are designed to mimic the process used to run the 24MS model (Reclamation 2015a). The current operational use of MTOM is to inform CRSS when generating 5-year projections (Reclamation provides the output of MTOM modeling upon request). Though the ability to use ensembles is advantageous for some purposes, MTOM cannot replace 24MS because current policy explicitly states that the most probable projections from 24MS will be used to set operations at Lakes Powell and Mead (U.S. Secretary of the Interior 2007; International Boundary and Water Commission 2017; Reclamation 2019c). Reclamation is currently working toward making MTOM projections more prominent and readily available.

Inflows

Like 24MS, MTOM runs are initialized with current reservoir conditions and the model takes unregulated streamflow forecasts as Upper Basin inflows. However, MTOM can use any number of hydrologic traces of 1 to 5 years in length instead of just one. MTOM's structure is almost identical to that of 24MS; it includes the same 12 reservoirs and inflow locations but has three additional forecast points in the Upper Basin: Yampa River at Deerlodge, Gunnison River gains between Crystal Reservoir and Grand Junction (including the North Fork of the Gunnison), and Animas River at Durango. These points were added to the model's structure and rule logic to automate a process that had been done manually in 24MS. Table 3.1 and the map in Figure 3.3 show these additional forecast points.

Demands

Water use and demands used in MTOM are also similar to those used in 24MS—only three Upper Basin diversions are projected in the model. However, the impacts of some use are represented in the unregulated flow forecasts provided by the CBRFC (see Chapters 5 and 8). Lower Basin demands are equal to the demand schedules provided by the Lower Basin states (Reclamation 2015a) in the current year of operations, and may be adjusted in the out years for different operating conditions.

MTOM is most commonly run using the 35 traces that make up the CBRFC's ESP forecasts but has more recently also been run with experimental forecasts (Baker 2019).

Output

MTOM output includes inflows, releases, reservoir contents, deliveries to water users, and indicators of operational conditions that are key to implementing the Interim Guidelines (Powell 2015). Currently, the most common use of MTOM is to initialize CRSS to produce 5-year projections of system conditions. See the "Development of five-year projections" section of this chapter for further information and an example of MTOM-CRSS output.

Colorado River Simulation System (CRSS)

Reclamation's first effort at computer simulation of the Colorado River system was in 1969, as part of studies to support the Long Range Operating Criteria negotiations (Reclamation 1969). That work was followed by Reclamation's development of the Colorado River Simulation Model in the 1970s, written in FORTRAN. A database of model inflows and demands was developed in the 1980s and the combined modeling tool—basin model plus database plus output utility—was called the Colorado River Simulation System, or CRSS (Reclamation 1983). CRSS was implemented in RiverWare in 1996 with essentially the same spatial and temporal resolution as the original FORTRAN model (Reclamation 2010). Over the years, features have been added to CRSS that have improved its user interface, analysis capabilities, database management system, and output summarization capabilities. CRSS is also updated to represent new or refined information about the system, e.g., physical relationships and new operational policies. Note that water salinity is also simulated in CRSS, but that capability is not discussed in this report.

CRSS enables Reclamation to explore impacts to the basin under different supply, demand, and policy configurations for years to decades into the future. It has been used for policy analyses in dozens of studies, including the Interim Guidelines EIS (Reclamation 2007f), the Basin Study (Reclamation 2012e), Minutes 319 and 323 (International Boundary and Water Commission 2012; 2017), and the Colorado River Basin Ten Tribes Partnership Tribal Water Study (Reclamation 2018). Most recently, it was used to provide guidance for basin-wide drought contingency planning (Reclamation 2019c). CRSS is currently being used in studies of how climate change hydrology derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) affects future projections (Chapter 11). It is also currently used in conjunction with 24MS or MTOM, or both, to generate official 5-year projections.

The Upper Basin reservoirs in CRSS are slightly different from those represented in 24MS and MTOM: Fontenelle, Flaming Gorge, Starvation (which is a lumped representation of multiple smaller reservoirs), Taylor Park, Blue Mesa, Morrow Point, Crystal, Navajo, and Powell (Vallecito is only in 24MS and MTOM while Starvation is only in CRSS). The Lower Basin reservoirs are the same: Mead, Mohave, and Havasu.

CRSS simulations always start in January. When running the model in any month other than January it is initialized using projections from the 24MS or MTOM of December 31 of the current year, and the CRSS simulations start in January of the following year. Reservoir operations are simulated via rulesets reflecting either current Law of the River or potential future alterations to operations.

Inflows

Of the 29 inflow points in CRSS, 14 are upstream of Reclamation's headwaters reservoirs and 15 are intervening flows along reaches within the model (Reclamation 2007a). The map in Figure 3.7 shows the inflow points represented in CRSS. The inflow points on the map correspond to the USGS gages listed in Table 3.1. Table 3.1 also describes the relationships between CRSS inflow points and the forecast points used in 24MS and MTOM.

Unlike the inflows to 24MS and MTOM, which are based on unregulated inflow forecasts from the CBRFC, CRSS uses natural flow as streamflow inputs. The terms "unregulated" and "natural" describe the level of upstream human activity remaining in the inflow datasets after naturalization calculations are made. The CBRFC unregulated inflows, described in detail in Chapters 5 and 8, are forecasted streamflows that are adjusted for upstream measured diversions, imports, and reservoir regulation. They do not account for upstream unmeasured uses or unmeasured return flows. In contrast, in the CRSS natural flow dataset, observed streamflows are naturalized by backing out both measured and unmeasured impacts, including consumptive uses, imports, and reservoir operations (see Chapter 5 for details about naturalization).

The CRSS streamflow paradigm allows Reclamation to simulate reservoir operations under long-term projections of both supply and demand. Hundreds of historical and theoretical inflow time-series or traces have been analyzed in CRSS to evaluate system impacts under different hydrologic assumptions. These assumptions generally fall into three categories: observed hydrology, paleohydrology, and climate change-informed hydrology. Development and use of data in each of these categories is described in detail in Chapters 5, 9, 10, and 11 of this report.

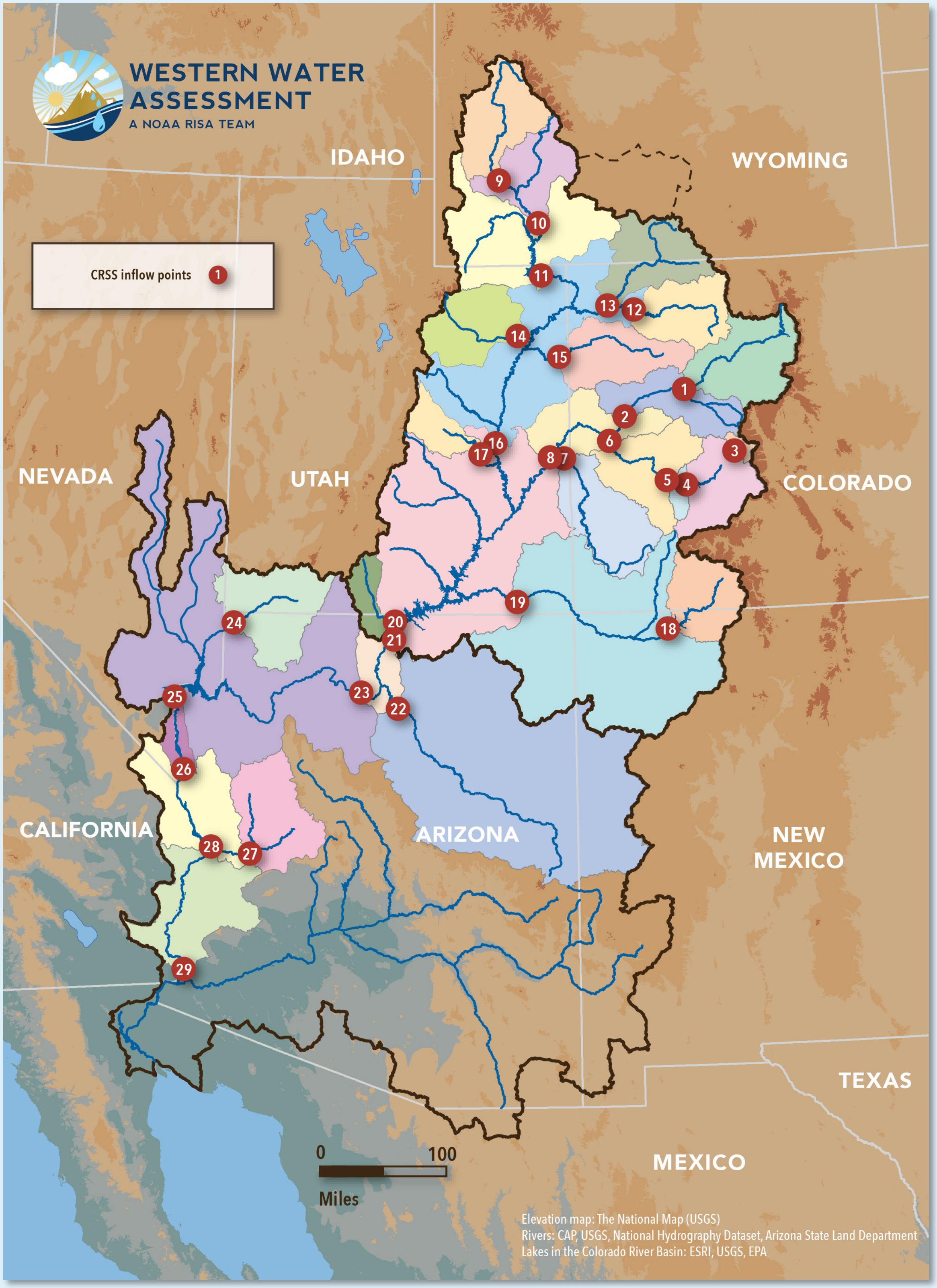

Figure 3.7
Map of CRSS inflow points. See Table 3.1 for details about each inflow location. (Source: Reclamation)

Demands

The 115 delivery points in CRSS represent about 500 water users throughout the basin across all sectors. In the Lower Basin, each mainstem user is individually represented. In the Upper Basin, nodes often represent spatial aggregations of many water users. To understand representation of water use in CRSS it is necessary to distinguish between demand (volume of water needed to meet identified uses), diversion (volume of water withdrawn from the river system), and depletion (volume of water that is diverted and not returned to the river after use). In the Upper Basin, long-term demand projections that increase over time are provided to Reclamation by the Upper Colorado River Commission (UCRC). The official projections currently used were developed in 2007. These demands are modeled in CRSS via diversion and depletion schedules provided by the states (Reclamation 2007d). The Upper Basin states produced updated depletion schedules in 2016 for eventual incorporation into Reclamation models (see callout box; S. McGettigan, pers. comm.). In exploratory studies, a variety of future demand scenarios are tested in CRSS to understand system response to climatic and social impacts on demands (Reclamation 2012b).

In CRSS, when there is not enough water, users in the Upper Basin experience shortage. Because CRSS does not model water allocation based on water rights, the Upper Basin shortages occur to the aggregated demands, irrespective of seniority, and therefore are not reported as shortages to individual demands.

For the Lower Basin states and Mexico, there are multiple diversion and depletion schedules that allow CRSS to model water use under surplus conditions, normal conditions, and the prescribed reductions under specific shortage conditions. Per the Interim Guidelines (U.S. Secretary of the Interior 2007), all Powell and Mead operating conditions are determined based on August projections of January 1 elevations. For long-term studies, CRSS does not replicate an August projection, it sets the upcoming year's operating conditions using its "actual" modeled January 1 reservoir contents. Additionally, the Lower Basin states and Mexico provide Intentionally Created Surplus (ICS) and Intentionally Created Mexican Allocation (ICMA) schedules and assumptions, respectively, that may increase or decrease deliveries in any given year.

Updated depletion schedules from UCRC

The currently used Upper Basin depletion schedule, dated December, 2007, is available here: http://www.ucrcommission.com/RepDoc/DepSchedules/Dep_Schedules_2007.pdf

And an updated depletion schedule, dated December, 2016, is available here: http://www.ucrcommission.com/RepDoc/DepSchedules/CurFutDemandSchedule.pdf.

Output

Typical CRSS simulations yield time series of reservoir releases, water surface elevations, hydropower generation, consumptive uses, and streamflows at select locations. The results of ensembles of runs are often summarized statistically to give a sense of the distribution of potential future conditions, as shown in Figure 3.8.

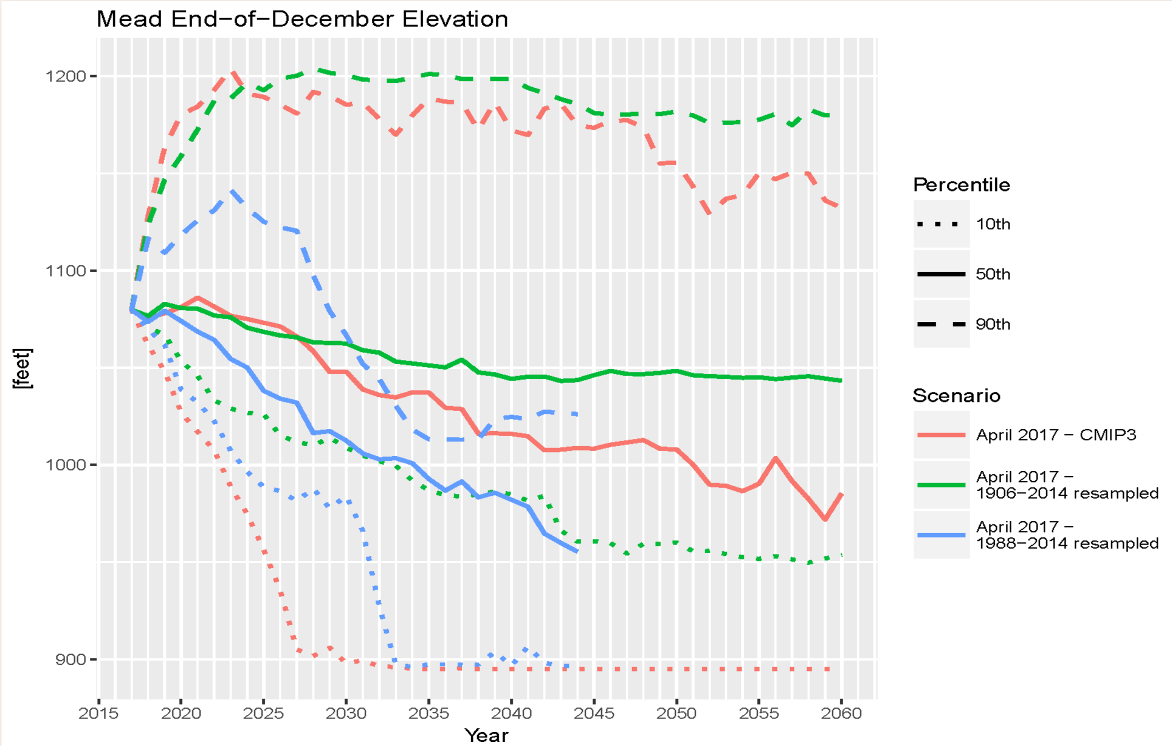

Figure 3.8

Example CRSS results. (Reclamation 2018)

Development of Five-Year Projections

For studies that look beyond Year 1, 24MS or MTOM is combined with CRSS to take advantage of the capabilities of all three models. A key example of this is the generation of official 5-year projections. The combined modeling approach for those studies is shown in Figure 3.9.

Because MTOM has demonstrated skill at 1- to 2-year lead times (Baker 2019), Reclamation uses it, with ESP forecasts, to simulate the first year, yielding 35 projections of end-of-year reservoir elevations. Those projections are then used to initialize CRSS. Each initialized CRSS run uses multiple, long-term naturalized flow traces generated by the index sequential method. (The index sequential method, or ISM, is described in Chapter 9.) Besides its demonstrated skill, an additional advantage to simulating the first year in MTOM is that it incorporates uncertainty during that year that, when combined with the ISM traces, represents a broader range of potential future conditions.

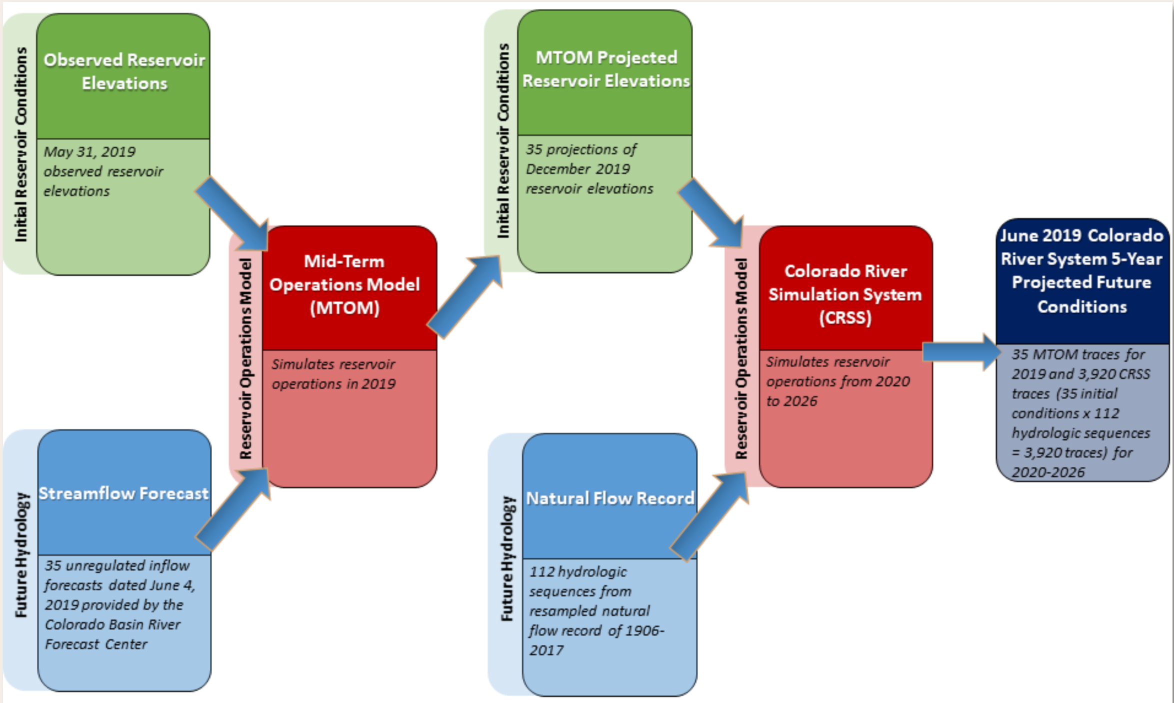

Figure 3.9

Schematic showing how MTOM and CRSS can be coupled to perform five-year projections. December 31 projections from 24MS are used instead of MTOM projections toward the end of the calendar year when there is little uncertainty. (Source: Reclamation website page "Colorado River System 5-Year Projected Future Conditions, https://www.usbr.gov/lc/region/g4000/riverops/crss-5year-projections.html, 2019)

Example output from combined MTOM-CRSS runs made in August, 2019 is provided in Figure 3.10 below. In this example, 35 unregulated inflow forecast traces from the CBRFC were used in MTOM to simulate 35 sets of potential December 31, 2019 reservoir elevations. These 35 sets provided a distribution of potential December 31, 2019 reservoir elevations and became the initial reservoir conditions used in CRSS, with ISM sequences, to simulate years 2020 through 2024. This modeling workflow generates a distribution of different operational conditions through 2024.

Percent of Traces with Event or System Condition. Results from August 2019 CRSS (Updated December 2019) using the Full Hydrology (resampling of the full natural flow record 1906-2017).

Event or System Condition	2020	2021	2022	2023	2024
Upper Basin - Lake Powell					
Equalization Tier (Powell >= Equalization [EQ] Elevation)	13	26	24	30	27
Equalization - annual release > 8.23 maf	13	26	24	29	26
Equalization - annual release = 8.23 maf	0	0	0	<1	<1
Upper Elevation Balancing Tier (Powell < EQ Elevation and >= 3,575 ft)	87	72	59	53	55
Upper Elevation Balancing - annual release > 8.23 maf	3	39	35	34	32
Upper Elevation Balancing - annual release = 8.23 maf	84	33	24	18	23
Upper Elevation Balancing - annual release < 8.23 maf	0	0	0	<1	0
Mid-Elevation Release Tier (Powell < 3,575 and >= 3,525 ft)	0	2	17	16	16
Mid-Elevation Release - annual release = 8.23 maf	0	0	0	0	2
Mid-Elevation Release - annual release = 7.48 maf	0	2	17	16	14
Lower Elevation Balancing Tier (Powell < 3,525 ft)	0	0	0	<1	2
Below Minimum Power Pool (Powell < 3,490 ft)	0	0	0	0	0
Lower Basin - Lake Mead					
Surplus Condition - any amount (Mead >= 1,145 ft)	0	0	7	12	19
Surplus - Flood Control	0	0	<1	3	3
Normal Year or ICS Surplus Condition (Mead < 1,145 and > 1,075 ft)	100	96	69	54	45
Recovery of DCP ICS / Mexico's Water Savings (Mead >/>= 1,110 ft)	0	9	19	27	32
DCP Contribution / Mexico's Water Savings (Mead <= 1,090 and > 1,075 ft)	100	70	44	31	25
Shortage Condition - any amount (Mead <= 1,075 ft)	0	4	24	33	37
Shortage / Reduction - 1st Level (Mead <= 1,075 and >= 1,050 ft)	0	4	24	26	23
DCP Contribution / Mexico's Water Savings (Mead <= 1,075 and >= 1,050 ft)	0	4	24	26	23
Shortage / Reduction - 2nd Level (Mead < 1,050 and >= 1,025 ft)	0	0	0	7	11
DCP Contribution / Mexico's Water Savings (Mead < 1,050 and > 1,045 ft)	0	0	0	3	6
DCP Contribution / Mexico's Water Savings (Mead <= 1,045 and > 1,040 ft)	0	0	0	2	<1
DCP Contribution / Mexico's Water Savings (Mead <= 1,040 and > 1,035 ft)	0	0	0	<1	2
DCP Contribution / Mexico's Water Savings (Mead <= 1,035 and > 1,030 ft)	0	0	0	2	<1
DCP Contribution / Mexico's Water Savings (Mead <= 1,030 and >=/> 1,025 ft)	0	0	0	0	<1
Shortage / Reduction - 3rd Level (Mead < 1,025 ft)	0	0	0	0	3
DCP Contribution / Mexico's Water Savings (Mead </<= 1,025 ft)	0	0	0	0	3

Figure 3.10

MTOM-CRSS output example. The figure shows the percent of traces with event or system condition. Results from August 2019 MTOM/CRSS using the full natural flow record. (1906–2017) (Source: Reclamation webpage "Colorado River System 5-Year Projected Future Conditions" https://www.usbr.gov/lc/region/g4000/riverops/crss-5year-projections.html

3.3 Uncertainty and error

The purpose of Reclamation modeling is to project future system conditions given varying inputs and operations. In the short-term, e.g., when running 24MS, the inputs are forecasts that incorporate *some* skillful knowledge of upcoming hydrology, water use, etc. For mid- and long-term modeling, inputs are based on ranges of *possible* futures. Any projection of the future is inherently uncertain, but uncertainty increases as projections go further out. Simplifications and assumptions required to model the system also introduce uncertainty into projections. Since both the input data and the representation of the system are imperfect, there are uncertainties at each step. Though each of the Reclamation models handles uncertainty differently, they are all impacted by four primary sources: streamflow, initial conditions, water use and demand, and reservoir operations.

Streamflow

Of the four sources, uncertainty in future streamflow has the largest impact on system projections. The three Reclamation models take inflows that have been developed through multiple methods applied to many different data types. Each inflow dataset has a provenance that reflects the availability of primary data, intermediate analytical techniques and models, and the goals of the application of the dataset. The inflow datasets are discussed in detail in Chapters 5, 8, 9, 10, and 11.

24MS and MTOM both currently use unregulated streamflow generated by the CBRFC. The observations, historical relationships, and assumptions built into their forecasting framework all aggregate into the streamflow Reclamation uses in its models. Reclamation contributes additional uncertainty to streamflow inputs to 24MS and MTOM by, for example, using historical averages for Lower Basin flows, calculating intervening flow through a mass balance calculation, and interpolating between CBRFC products. For studies using 24MS, uncertainty is acknowledged four times per year by simulating probable minimum and maximum hydrology (in January, April, August, and October). Annual Year 1 streamflow uncertainty decreases throughout the year as snowpack and temperature conditions develop. The case is the same with MTOM, although it is always run with ensemble hydrology and results are presented as probabilistic views of a range of possible outcomes rather than as a single outcome.

Historical natural flow used in CRSS has different sources of uncertainty than unregulated flow. It is a purely derived product; Reclamation uses data collected from USGS and other operators' gage sites, consumptive use records, records of reservoir storage and releases, and other data to compute the natural flow. Simplifications in all of these data sources propagate through the computation. Intervening natural flows have additional uncertainty because they are calculated via mass balance between measured flows and become catchalls for residual errors in groundwater interactions and non-natural components of the upstream inflows, such as reservoir evaporation and bank storage, rather than reflecting natural gains and losses exclusively. Reclamation is aware of these issues; their work plan includes additions or refinements to estimates of Upper Basin irrigated acreage and evapotranspiration, Lower Basin consumptive use, and both Lake Powell and Lake Mead evaporation.

Although the historical natural flow uncertainties described above do exist, CRSS is also often driven by synthetic hydrologic inputs that attempt to capture long-term changes. To the extent that the synthetic hydrology is independent of the natural flows, uncertainties in generating natural flows become less relevant, though synthetic flows also carry some level of uncertainty depending on how they were developed.

Initial conditions

24MS and MTOM are always initiated with current reservoir conditions so initial conditions are not a source of uncertainty for these models. CRSS is initialized with December 31 projections of the current year from either 24MS or MTOM. Specifically, for the August CRSS run only one set of initial conditions from the 24MS model are used because there is little uncertainty in the end-of-calendar-year reservoir elevations and because the coordinated reservoir operations for the upcoming year are determined by that 24MS run. In any other month, the CRSS initial conditions are taken from a set of 35 MTOM projections. This uncertainty is intentional and enables Reclamation to present a broader range of potential future conditions.

Water use and demand

In 24MS and MTOM, the only representations of Upper Basin water use are the implicit unmeasured depletions and return flows left in CBRFC's unregulated flow forecasts and the three diversions described in previous sections. As such, the uncertainty about water use is a function of Upper Basin unmeasured depletions and return flows and Reclamation's or water users' projections of the three diversions. In the Lower Basin, water users provide monthly water use schedules. The uncertainty in Year 1 Lower Basin water use can be significant early in the year but decreases as the year progresses. Sources of water use and demand uncertainty are similar in MTOM, but most projections are based on historical schedules and embedded model logic so the uncertainty does not decrease over time.

Water demand assumptions for CRSS are provided by the Upper and Lower Basin states and key water users throughout the basin. Significant uncertainty exists when projecting future demand, but this uncertainty is greater in the Upper Basin than in the Lower Basin because Lower Basin water users have reached their full apportionments. Incomplete records of historical demand in the Upper Basin (as opposed to consumptive use, which is computed) further confound this issue because it is difficult to know how much projected demand deviates from historical demand. To address this uncertainty, the 2012 Basin Study (Reclamation 2012e) adopted a scenario planning approach to project future basin-wide water demand. The application of such an approach represents a new paradigm in the basin and a significant advancement in basin long-term planning. Reclamation and the basin states recognize the importance of continued refinement of scenario planning as part of a robust long-term planning framework for the basin.

Reservoir operations

Reclamation's models must represent complex operating policies, some of which are at sub-monthly timescales, through rules, which introduce uncertainty into projections. Some sources of uncertainty can be reduced with sufficient information and some cannot (e.g., adaptive management provisions for reservoirs or futures where no operational detail is provided). Reclamation has begun using hindcasts to identify sources of uncertainty that can be addressed. Hindcasts are performed by initializing a model to a historical state and using perfect knowledge of "future" conditions as inputs. This allows Reclamation to differentiate model uncertainty from input uncertainty.

Current estimates of projection uncertainty

One approach to understanding uncertainty in Reclamation projections is to compare the results of 24MS most probable runs to what actually occurred. This is the equivalent of quantifying error in the projections due to all uncertainties combined. Figure 3.11 shows the evolution of error in reservoir elevation projections for 24MS runs performed each month for the years 2008 to 2014 (Reclamation 2019b). The outlook length is longest on the left hand side of the plot (i.e., the January projection of the December 31st elevation 24 months in the future) and the lead time decreases going toward the right hand side of the plot. Error is highest at longer lead times and decreases over the course of the monthly projections. The projected year, e.g., 2013, is used as the symbol indicating how accurate each projection of that year was from 24 months in advance to the simulation performed in December 2013. For example, because 2013 was a dry year, the projection of Lake Powell's elevation 24 months in advance (i.e., the projection made in January 2011) was far higher than the eventual elevation.

In general, 24MS projections are more accurate at shorter lead times, though there are exceptions. The largest errors occurred in extreme years: 2011 was very wet while 2012 and 2013 were very dry. The year 2011 also demonstrates how, when the forecasted Lake Powell inflow results in a change of projected operating tiers, there can be significant implications for the skill of Lake Mead projections. August end of calendar year projections, highlighted in green, averaged less than 2 feet of error for the 2008 to 2014 period.

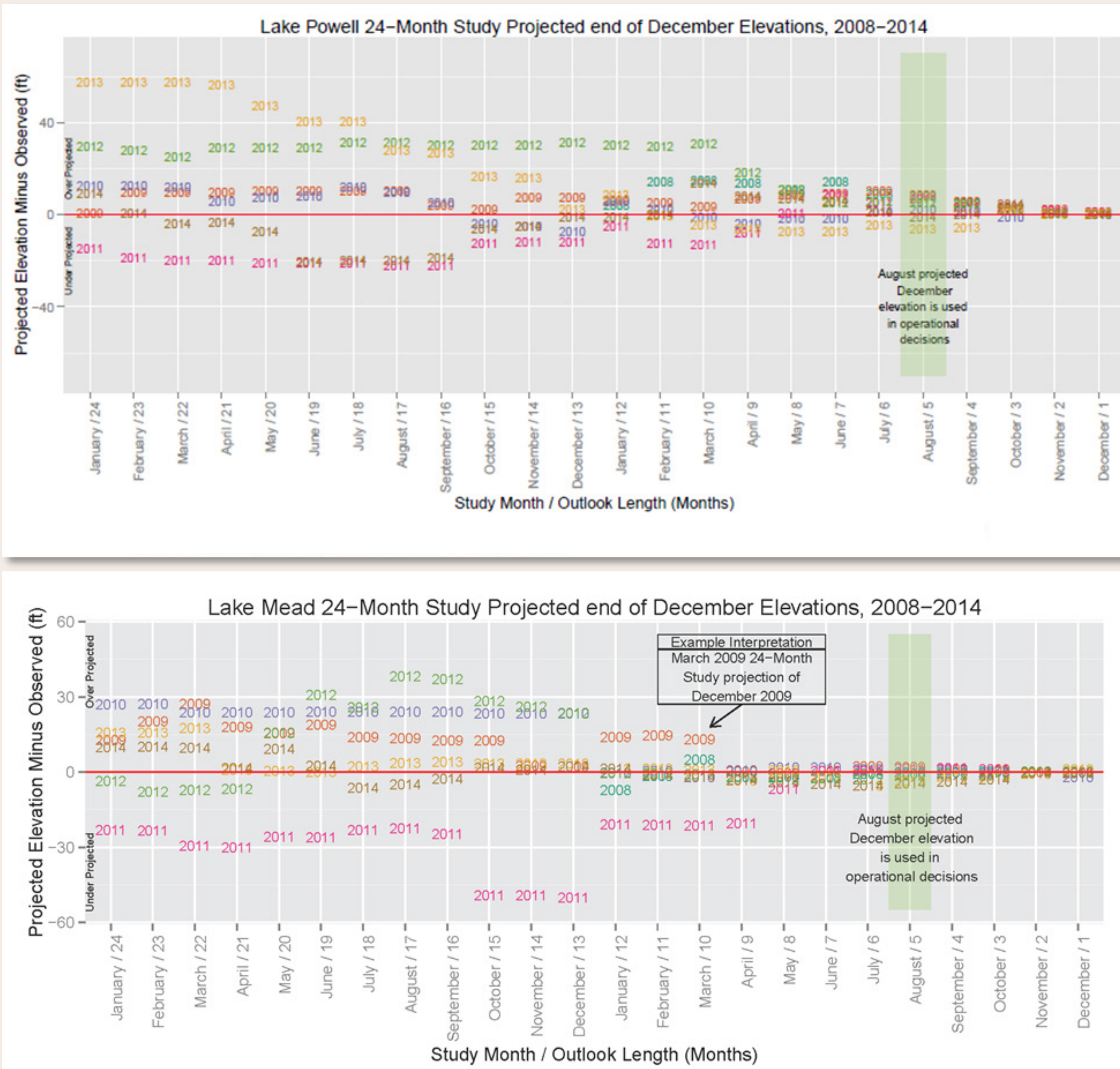

Figure 3.11

Projections of Lakes Powell and Mead EOCY elevation compared with observed values from various outlook lengths (each point represents a projection of December of the year shown) for the period 2008-2014. (Source: Reclamation 2019b).

It is important to understand these errors and reduce uncertainty where possible because of the decision-making context of 24MS. Reservoir projections used in tier determinations can be sensitive to fairly small errors in inputs to 24MS, particularly when Lake Powell or Lake Mead elevations are hovering near tier thresholds. For example, 24MS currently uses 5-year running average values for intervening flows between Lake Powell and Lake Mead. Observed intervening flows can deviate from those averages enough to change Mead's elevation by a few feet, potentially moving it from normal to shortage operations or vice versa (FROMUS; Reclamation and Colorado Basin River Forecast Center in preparation).

As discussed above, the importance of the uncertainty underlying MTOM and CRSS projections is conceptually different from how it impacts 24MS because they were developed to assess risk under uncertainty. Additionally, CRSS is often used to compare risks under different future supply, demand, or operations scenarios, i.e., it is used to evaluate the sensitivity of the system to different inputs or assumptions (Reclamation 2012e).

Ongoing efforts to address uncertainty

In addition to the efforts mentioned under specific headings above, Reclamation is engaged in multiple projects to identify, reduce, or account for uncertainty in each of the three models. In collaboration with the CBRFC, Reclamation is preparing a report identifying the sources of error and uncertainty associated with 24MS. The draft Forecast and Reservoir Operation Modeling Uncertainty Scoping report (Reclamation and Colorado Basin River Forecast Center in preparation) addresses over a dozen parameters, summarizes the cost and time required to reduce the error and uncertainty in each of them, and estimates the impact that reduction would have on 24MS projections.

A version of MTOM was adapted to be run in "verification mode" to produce hindcasts as part of recently completed research that uses MTOM as a testbed for experimental hydrology forecasts (Baker 2019). Results of the hindcasting are currently being drafted in a Reclamation report. MTOM will continue to be refined as further studies are completed.

A CRSS verification model has also been developed, but hindcast studies are in preliminary phases. Finally, because long-term hydrologic uncertainty is extremely large and cannot be reduced, Reclamation continues to explore decision-making under deep uncertainty (DMDU) methods similar to the robustness concepts used during the 2012 Basin Study (Reclamation 2012e).

3.4 Limitations due to simplification

All models of river basin systems have limitations because they are simplifications, in both space and time, of complex physical and institutional processes. Simplification is clearly reasonable but it can introduce error that affects the ability of Reclamation and others to accurately simulate the Colorado River Basin and limits the level of analysis that can be performed.

Representation of natural flows in the Upper Basin

Natural flows in the Upper Basin are represented by aggregating large runoff-producing areas on the Colorado, Green, and San Juan rivers. This level of spatial resolution was set with the original FORTRAN model built in the 1980s (Reclamation 1983) and has changed very little (the current version contains an additional inflow point on the Taylor River). Wheeler, Rosenberg, and Schmidt (2019) describe in detail the implications of both the spatial and temporal resolution on the utility of CRSS for particular types of analyses in the Upper Basin. They assert that the coarse resolution of CRSS in the Upper Basin 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" (Wheeler, Rosenberg, and Schmidt 2019). It is also true, however, that CRSS was not designed to perform those types of analyses and was rather designed as a tool for long-range basin planning centered on the federal reservoirs. The impacts of CRSS's coarse resolution in the Upper Basin on scenario outcomes have not been studied.

The development and limitations of natural flows are discussed in further detail in Chapter 5.

Representation of natural flows in the Lower Basin

The treatment of Lower Basin tributaries in CRSS limits the ability to fully assess the natural water supply of the basin (Reclamation 2012e). For four of the inflow points below Lees Ferry (the Paria, Little Colorado, Virgin, and Bill Williams rivers), CRSS uses historical inflows (not natural flows) based on USGS streamflow gages. In addition, the Gila River is not included in CRSS, making the uncertainties associated with the Gila River and the other Lower Basin tributaries and how they may contribute to system reliability difficult to discern (Lukas, Wade, and Rajagopalan 2013).

Since the 2012 Basin Study, Reclamation has been engaged in efforts to 1) resolve and correct, in collaboration with the basin states, the methodological and data inconsistencies in Reclamation's Consumptive Uses and Losses Reports pertaining to all of the Lower Basin tributaries (Reclamation "Plans & Reports" n.d.); 2) develop natural flows for the Little Colorado, Virgin and Bill Williams rivers and modify CRSS to use natural flows for those tributaries; and 3) explore the feasibility and usefulness of computing natural flows for the Gila River Basin and the feasibility and usefulness of adding that basin to CRSS. See Basin Study supplements Appendix C11 and Tech Report C (Reclamation 2012a; 2012d) for more-detailed discussions of these issues.

Representation of the physical and institutional setting

The spatial and temporal detail of CRSS (and 24MS and MTOM) limit the ability to assess impacts to basin resources, in particular water deliveries and shortages in the Upper Basin and ecological resources (Reclamation 2012e). For example, over 4,000 square miles of watershed above Glenwood Springs are simplified, lumping headwater reservoir operations, major exports to the Front Range, and over 100,000 acres of irrigated agriculture at one node. Limitations due to the spatial simplifications of CRSS are also described by Wheeler, Rosenberg, and Schmidt (2019). Such simplifications require that natural systems are evaluated through approximations at larger spatial scales and longer time steps (e.g., monthly versus daily) than preferred or required for more detailed assessments.

Simplifications in CRSS's institutional representation of the basin also result in limitations. For example, CRSS tracks shortages in the Upper Basin when the flow is insufficient to meet the local demands as opposed to simulating the complex water rights system in each state that would be needed to appropriately model shortages to individual water rights holders. In addition, CRSS does not have the capability to assign Upper Basin shortages in the event that a "Compact Call" is modeled; in such cases CRSS injects deficit water directly above Lake Powell.

The implications of this limitation were made clear in the 2012 Basin Study and in the 2018 Ten Tribes Partnership Study. During the 2012 Basin Study analyses, it was discovered that two senior downstream water rights in Colorado were subject to shortages in the model despite their priority, because CRSS allocates water sequentially from upstream to downstream. This issue was identified and rectified by modifying CRSS to ensure that these two particular senior rights (the Shoshone Power Plant and the senior users from the Grand Valley Irrigation Company) were satisfied before upstream rights received water (Reclamation 2012f). In the 2018 Ten Tribes Partnership Study, to partially address the water rights concern, the CRSS representation of a tribal diversion on the Duchesne River was moved upstream to ensure that it received its senior allocation, and the State of Colorado's StateMod model was used for simulation of tribal rights on the San Juan River in order to ensure the proper allocation to water rights in that basin (Reclamation 2018).

The general areas of uncertainty, error, and limitations noted above begin with the input data and extend through the representation of the institutional setting. As noted, in most cases, the areas present opportunities for additional research and development and improvement of model representation and available data. Reclamation continues to pursue these opportunities, as appropriate, in an effort to continually improve their modeling capabilities.

3.5 Challenges and opportunities

Challenge

Each Reclamation model (24MS, MTOM, and CRSS) has different ways that uncertainty can be better quantified and either addressed or incorporated. In particular, each model uses a more simplistic method for projecting future inflows in the Lower Basin than in the Upper Basin (5-year averages for 24MS and MTOM rather than a forecast, and gaged flow in CRSS rather than natural flow). In the Upper Basin, demand projections may differ from actual water use trends and the representation of complex operating policies via rules deployed at the monthly time step may further contribute to this deviation. Finally, more in-depth analyses are needed to verify how well modeled operational policies reflect actual operations. (Challenges associated with hydrologic uncertainty are described in Chapters 5, 8, 9, 10, and 11.)

Opportunities

- Complete FROMUS report and update its findings as models are refined.
- Work with the CBRFC to develop unregulated flow forecasts for the Lower Basin.
- Continue to work toward commitments outlined in the Colorado River Basin Study regarding the development of natural flows in the Lower Basin.
- Work with Upper Basin states, water users, and tribes to refine long-term demand projections.
- Complete hindcasting studies that can help identify how simplifications in Reclamation's models contribute to projection error.

Challenge

The coarse spatial resolution in CRSS has implications for studying demands and tributary flows. In the Upper Basin, water demands are represented in highly aggregated nodes and do not reflect water right priorities, which limits the ability to accurately model shortages to specific users under different scenarios. On the Lower Basin tributaries, because gaged flow is used rather than natural flow, demands are not explicitly modeled. CRSS uses a monthly time step that limits the ability to analyze the impacts to certain resources, in particular, ecological resources. Additionally, the exclusion of smaller tributaries limits the analyses that can be performed with CRSS.

Opportunities

- Review the configuration, number of nodes, and rules in the Upper Basin to explore implementing an allocation system that captures the distribution of water supply by water rights priority.
- The quality, coverage, and resolution of data that is used to naturalize inflows has improved and might support model disaggregation in both time and space.
- Explore iterative sub-basin implementations that are solved at shorter time scales or finer resolutions and that may be aggregated and fed into existing nodes in CRSS.

Challenge

Reclamation models are complex and the projections they generate are the product of combinations of many data sources and assumptions. It is critical that stakeholders and the public understand the uncertainty and how this uncertainty affects projections of risk in order to ensure the appropriate use of the results for decision making. Reclamation continues to work toward improving such communication but there is room for improvement. Additionally, the models are not comprehensively documented, despite their critical importance in Colorado River Basin management and planning.

Opportunities

- Continue to improve and refine communication of model assumptions and uncertainty on Reclamation's modeling website and in widely distributed modeling results (e.g., the 24MS reports).
- Develop comprehensive, technical overviews of each of the models to share how each model is configured, how the rules are implemented, and how the inputs are derived.

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Glossary

ablation
The loss of snow from the snowpack due to melting, evaporation, or wind.

absolute error
The difference between the measured and actual values of *x*.

albedo
The percentage of incoming light that is reflected off of a surface.

aleatory uncertainty
Uncertainty due to randomness in the behavior of a system (i.e., natural variability)

anomaly
A deviation from the expected or normal value.

atmospheric river (AR)
A long and concentrated plume of low-level (<5,000') moisture originating in the tropical Pacific.

autocorrelation
Correlation between consecutive values of the same time series, typically due to time-dependencies in the dataset.

bank storage
Water that seeps into and out of the bed and banks of a stream, lake, or reservoir depending on relative water levels.

bias correction
Adjustments to raw model output (e.g., from a climate model, or streamflow forecast model) using observations in a reference period.

boundary conditions
Conditions that govern the evolution of climate for a given area (e.g., ocean heat flux, soil moisture, sea-ice and snowpack conditions) and can help forecast the future climate state when included in a model.

calibration
The process of comparing a model with the real system, followed by multiple revisions and comparisons so that the model outputs more closely resemble outcomes in the real system.

climate forcing
A factor causing a difference between the incoming and outgoing energy of the Earth's climate system, e.g., increases in greenhouse-gas concentrations.

climatology
In forecasting and modeling, refers to the historical average climate used as a baseline (e.g., "compared to climatology"). Synonymous with climate normal.

coefficient of variation (CV)
A common measure of variability in a dataset; the standard deviation divided by the mean.

consumptive use
The amount of diverted water that is lost during usage via evapotranspiration, evaporation, or seepage and is thus unavailable for subsequent use.

convection
The vertical transport of heat and moisture in the atmosphere, typically due to an air parcel rising if it is warmer than the surrounding atmosphere.

covariate
A variable (e.g., temperature) whose value changes when the variable under study changes (e.g., precipitation).

cross-correlation
A method for estimating to what degree two variables or datasets are correlated.

cumulative distribution function (CDF)
A function describing the probability that a random variable, such as streamflow, is less than or equal to a specified value. CDF-based probabilities are often expressed in terms of percent exceedance or non-exceedance.

Darcy's Law
The mathematical expression that describes fluid flow through a porous medium (e.g., soil).

datum
The base, or 0.0-foot gage-height (stage), for a stream gage.

dead pool
The point at which the water level of a lake or reservoir is so low, water can no longer be discharged or released downstream.

deterministic
Referring to a system or model in which a given input always produces the same output; the input strictly determines the output.

dewpoint
The local temperature that the air would need to be cooled to (assuming atmospheric pressure and moisture content are constant) in order to achieve a relative humidity (RH) of 100%.

dipole
A pair of two equal and opposing centers of action, usually separated by a distance.

discharge
Volume of water flowing past a given point in the stream in a given period of time; synonymous with streamflow.

distributed
In hydrologic modeling, a distributed model explicitly accounts for spatial variability by dividing basins into grid cells. Contrast with **lumped** model.

downscaling
Method to take data at coarse scales, e.g., from a GCM, and translate those data to more local scales.

dynamical
In modeling, refers to the use of a physical model, i.e., basic physical equations represent some or most of the relevant processes.

environmental flow
Water that is left in or released into a river to manage the quantity, quality, and timing of flow in order to sustain the river's ecosystem.

epistemic uncertainty
Uncertainty due to incomplete knowledge of the behavior of a system.

evapotranspiration
A combination of evaporation from the land surface and water bodies, and transpiration of water from plant surfaces to the atmosphere. Generally includes sublimation from the snow surface as well.

fixed lapse rate
A constant rate of change of an atmospheric variable, usually temperature, with elevation.

flow routing
The process of determining the flow hydrograph at sequential points along a stream based on a known hydrograph upstream.

forcing - see **climate forcing or weather forcing**

forecast
A prediction of future hydrologic or climate conditions based on the initial (current) conditions and factors known to influence the evolution of the physical system.

Gaussian filter
A mathematical filter used to remove noise and emphasize a specific frequency of a signal; uses a bell-shaped statistical distribution.

gridded data
Data that is represented in a two-dimensional gridded matrix of graphical contours, interpolated or otherwise derived from a set of point observations.

heat flux
The rate of heat energy transfer from one surface or layer of the atmosphere to the next.

hindcast
A forecast run for a past date or period, using the same model version as for real-time forecasts; used for model calibration and to "spin up" forecast models. Same as **reforecast**.

hydraulic conductivity
A measure of the ease with which water flows through a medium, such as soil or sediment.

hydroclimate
The aggregate of climatic and hydrologic processes and characteristics, and linkages between them, for a watershed or region.

hydrograph
A graph of the volume of water flowing past a location per unit time.

hydrometeorology
A branch of meteorology and hydrology that studies the transfer of water and energy between the land surface and the lower atmosphere.

imaging spectrometer
An instrument used for measuring wavelengths of light spectra in order to create a spectrally-resolved image of an object or area.

in situ
Referring to a ground-based measurement site that is fixed in place.

inhomogeneity
A change in the mean or variance of a time-series of data (such as weather observations) that is caused by changes in the observing station or network, not in the climate itself.

Interim Guidelines
The Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, signed by the Secretary of the Interior in December 2007. The guidelines expire in 2026. https://www.usbr.gov/lc/region/programs/strategies.html

internal variability
Variability in climate that comes from chaotic and unpredictable fluctuations of the Earth's oceans and atmosphere.

interpolation
The process of calculating the value of a function or set of data between two known values.

isothermal
A dynamic in which temperature remains constant while other aspects of the system change.

jet stream
A narrow band of very strong winds in the upper atmosphere that follows the boundary between warmer and colder air masses.

kriging
A smoothing technique that calculates minimum error-variance estimates for unsampled values.

kurtosis
A measure of the sharpness of the peak of a probability distribution.

lag-1 autocorrelation
Serial correlation between data values at adjacent time steps.

lapse rate
The rate of change of an atmospheric variable, such as temperature, with elevation. A lapse rate is adiabatic when no heat exchange occurs between the given air parcel and its surroundings.

latency
The lag, relative to real-time, for producing and releasing a dataset that represents real-time conditions.

latent heat flux
The flow of heat from the Earth's surface to the atmosphere that involves evaporation and condensation of water; the energy absorbed/released during a phase change of a substance.

Law of the River
A collection of compacts, federal laws, court decisions and decrees, contracts, and regulatory guidelines that apportions the water and regulates the use and management of the Colorado River among the seven basin states and Mexico.

LiDAR (or lidar)
Light detection and ranging; a remote sensing method which uses pulsed lasers of light to measure the variable distances from the sensor to the land surface.

longwave radiation
Infrared energy emitted by the Earth and its atmosphere at wavelengths between about 5 and 25 micrometers.

Lower Basin
The portions of the Colorado River Basin in Arizona, California, Nevada, New Mexico and Utah that are downstream of the Colorado River Compact point at Lee Ferry, Arizona.

lumped model
In hydrologic modeling, a lumped model represents individual sub-basins or elevation zones as a single unit, averaging spatial characteristics across that unit. Contrast with **distributed model.**

Markov chain
A mathematical system in which transitions from one state to another are dependent on the current state and time elapsed.

megadrought
A sustained and widespread drought that lasts at least 10-15 years, though definitions in the literature have varied.

metadata
Data that gives information about other data or describes its own dataset.

mid-latitude cyclone
A large (~500-2000 km) storm system that has a low-pressure center, cyclonic (counter-clockwise) flow, and a cold front. Over the western U.S., mid-latitude cyclones almost always move from west to east and are effective at producing precipitation over broad areas.

Minute 319
The binding agreement signed in 2012 by the International Boundary and Water Commission, United States and Mexico, to advance the 1944 Water Treaty between both countries and establish better basin operations and water allocation, and humanitarian measures.

Modoki
An El Niño event that has its warmest SST anomalies located in the central equatorial Pacific; same as "CP" El Niño.

multicollinearity
A condition in which multiple explanatory variables that predict variation in a response variable are themselves correlated with each other.

multiple linear regression
A form of regression in which a model is created by fitting a linear equation over the observed data, typically for two or more explanatory (independent) variables and a response (dependent) variable.

multivariate
Referring to statistical methods in which there are multiple response (dependent) variables being examined.

natural flow
Gaged flow that has been adjusted to remove the effects of upstream human activity such as storage or diversion. Equivalent to **naturalized flow**, **virgin flow**, and **undepleted flow**.

naturalized flow – see *natural flow*

nearest neighbor method
A nonparametric method that examines the distances between a data point (e.g., a sampled value) and the closest data points to it in *x-y* space ("nearest neighbors," e.g., historical values) and thereby obtains either a classification for the data point (such as wet, dry, or normal) or a set of nearest neighbors (i.e., K-NN).

nonparametric
A statistical method that assumes no underlying mathematical function for a sample of observations.

orographic lift
A process in which air is forced to rise and subsequently cool due to physical barriers such as hills or mountains. This mechanism leads to increased condensation and precipitation over higher terrain.

p
A statistical hypothesis test; the probability of obtaining a particular result purely by chance; a test of statistical significance.

paleohydrology
The study of hydrologic events and processes prior to the instrumental (gaged) record, typically using environmental proxies such as tree rings.

parameterized
Referring to a key variable or factor that is represented in a model by an estimated value (**parameter**) based on observations, rather than being explicitly modeled through physical equations.

parametric
A statistical method that assumes an underlying mathematical function, specified by a set of characteristics, or parameters (e.g., mean and standard deviation) for a sample of observations.

persistence
In hydrology, the tendency of high flows to follow high flows, and low flows to follow low flows. Hydrologic time series with persistence are **autocorrelated**.

phreatophytes
Plants with deep root systems that are dependent on water from the water table or adjacent soil moisture reserves.

pluvial
An extended period, typically 5 years or longer, of abnormally wet conditions; the opposite of drought.

principal components regression (PCR)
A statistical technique for analyzing and developing multiple regressions from data with multiple potential explanatory variables.

prior appropriation
"First in time, first in right." The prevailing doctrine of water rights for the western United States; a legal system that determines water rights by the earliest date of diversion or storage for beneficial use.

probability density function (PDF)
A function, or curve, that defines the shape of a probability distribution for a continuous random variable.

projection
A long-term (typically 10-100 years) forecast of future hydroclimatic conditions that is contingent on specified other conditions occurring during the forecast period, typically a particular scenario of greenhouse gas emissions.

quantiles
Divisions of the range of observations of a variable into equal-sized groups.

r
Correlation coefficient. The strength and direction of a linear relationship between two variables.

R^2
Coefficient of determination. The proportion of variance in a dependent variable that's explained by the independent variables in a regression model.

radiometer
An instrument used to detect and measure the intensity of radiant energy, i.e., shortwave energy emitted from the sun and reflected by clouds, and longwave energy emitted from the earth's surface.

raster
A digital image or computer mapping format consisting of rows of colored pixels.

reanalysis
An analysis of historical climate or hydrologic conditions that assimilates observed data into a modeling environment to produce consistent fields of variables over the entire period of analysis.

reference evapotranspiration
An estimate of the upper bound of evapotranspiration losses from irrigated croplands, and thereby the water need for irrigation.

regression
A statistical technique used for modeling the linear relationship between two or more variables, e.g., snowpack and seasonal streamflow.

relative humidity (RH)
The amount of moisture in the atmosphere relative to the amount that would be present if the air were saturated. RH is expressed in percent, and is a function of both moisture content and air temperature.

remote sensing
The science and techniques for obtaining information from sensors placed on satellites, aircraft, or other platforms distant from the object(s) being sensed.

residual
The difference between the observed value and the estimated value of the quantity of interest.

resolution
The level of detail in model output; the ability to distinguish two points in space (or time) as separate.

> *spatial resolution* - Resolution across space, i.e., the ability to separate small details in a spatial representation such as in an image or model.
> *temporal resolution* - Resolution in time, i.e., hourly, daily, monthly, or annual. Equivalent to time step.

return flow
The water diverted from a river or stream that returns to a water source and is available for consumptive use by others downstream.

runoff
Precipitation that flows toward streams on the surface of the ground or within the ground. Runoff as it is routed and measured within channels is *streamflow*.

runoff efficiency
The fraction of annual precipitation in a basin or other area that becomes runoff, i.e., not lost through evapotranspiration.

sensible heat flux
The flow of heat from the Earth's surface to the atmosphere without phase changes in the water, or the energy directly absorbed/released by an object without a phase change occurring.

shortwave radiation
Incoming solar radiation consisting of visible, near-ultraviolet, and near-infrared spectra. The wavelength spectrum is between 0.2 and 3.0 micrometers.

skew
The degree of asymmetry in a given probability distribution from a Gaussian or normal (i.e., bell-shaped) distribution.

skill
The accuracy of the forecast relative to a baseline "naïve" forecast, such as the climatological average for that day. A forecast that performs better than the baseline forecast is said to have positive skill.

smoothing filter
A mathematical filter designed to enhance the signal-to-noise ratio in a dataset over certain frequencies. Common signal smoothing techniques include moving average and Gaussian algorithms.

snow water equivalent (SWE)
The depth, often expressed in inches, of liquid water contained within the snowpack that would theoretically result if you melted the snowpack instantaneously.

snow course
A linear site used from which manual measurements are taken periodically, to represent snowpack conditions for larger area. Courses are typically about 1,000' long and are situated in areas protected from wind in order to get the most accurate snowpack measurements.

snow pillow
A device (e.g., at SNOTEL sites) that provides a value of the average water equivalent of snow that has accumulated on it; typically the pillow contains antifreeze and has a pressure sensor that measures the weight pressing down on the pillow.

stationarity
The condition in which the statistical properties of the sample data, including their probability distribution and related parameters, are stable over time.

statistically significant
Unlikely to occur by chance alone, as indicated by one of several statistical tests.

stepwise regression
The process of building a regression model from a set of values by entering and removing predictor variables in a step-by-step manner.

stochastic method
A statistical method in which randomness is considered and included in the model used to generate output; the same input may produce different outputs in successive model runs.

stratosphere
The region of the upper atmosphere extending from the top of the troposphere to the base of the mesosphere; it begins about 11–15 km above the surface in the mid-latitudes.

streamflow
Water flow within a river channel, typically expressed in cubic feet per second for flow rate, or in acre-feet for flow volume. Synonymous with **discharge**.

sublimation
When water (i.e., snow and ice) or another substance transitions from the solid phase to the vapor phase without going through the intermediate liquid phase; a major source of snowpack loss over the course of the season.

surface energy balance
The net balance of the exchange of energy between the Earth's surface and the atmosphere.

teleconnection
A physical linkage between a change in atmospheric/oceanic circulation in one region (e.g., ENSO; the tropical Pacific) and a shift in weather or climate in a distant region (e.g., the Colorado River Basin).

temperature inversion
When temperature increases with height in a layer of the atmosphere, as opposed to the typical gradient of temperature decreasing with height.

tercile
Any of the two points that divide an ordered distribution into three parts, each containing a third of the population.

tilt
A shift in probabilities toward a certain outcome.

transpiration
Water discharged into the atmosphere from plant surfaces.

troposphere
The layer of the atmosphere from the Earth's surface up to the tropopause (~11–15 km) below the stratosphere; characterized by decreasing temperature with height, vertical wind motion, water vapor content, and sensible weather (clouds, rain, etc.).

undercatch
When less precipitation is captured by a precipitation gage than actually falls; more likely to occur with snow, especially under windy conditions.

unregulated flow
Observed streamflow adjusted for some, but not all upstream activities, depending on the location and application.

Upper Basin
The parts of the Colorado River Basin in Colorado, Utah, Wyoming, Arizona, and New Mexico that are upstream of the Colorado River Compact point at Lee Ferry, Arizona.

validation
The process of comparing a model and its behavior and outputs to the real system, after calibration.

variance
An instance of difference in the data set. In regard to statistics, variance is the square of the standard deviation of a variable from its mean in the data set.

wavelet analysis
A method for determining the dominant frequencies constituting the overall time-varying signal in a dataset.

Acronyms & Abbreviations

24MS
24-Month Study Model

AET
actual evapotranspiration

AgriMET
Cooperative Agricultural Weather Network

AgWxNet
Agricultural Weather Network

AHPS
Advanced Hydrologic Prediction Service

ALEXI
Atmosphere-Land Exchange Inversion

AMJ
April-May-June

AMO
Atlantic Multidecadal Oscillation

ANN
artificial neural network

AOP
Annual Operating Plan

AR
atmospheric river

AR-1
first-order autoregression

ARkStorm
Atmospheric River 1,000-year Storm

ASCE
American Society of Civil Engineers

ASO
Airborne Snow Observatory

ASOS
Automated Surface Observing System

AVHRR
Advanced Very High-Resolution Radiometer

AWOS
Automated Weather Observing System

BCCA
Bias-Corrected Constructed Analog

BCSD
Bias-Corrected Spatial Disaggregation (downscaling method)

BCSD5
BCSD applied to CMIP5

BOR
United States Bureau of Reclamation

BREB
Bowen Ratio Energy Balance method

C3S
Copernicus Climate Change Service

CA
Constructed Analogues

CADSWES
Center for Advanced Decision Support for Water and Environmental Systems

CADWR
California Department of Water Resources

CanCM4i
Canadian Coupled Model, 4th generation (global climate model)

CBRFC
Colorado Basin River Forecast Center

CCA
Canonical Correlation Analysis

CCSM4
Community Climate System Model, version 4 (global climate model)

CDEC
California Data Exchange Center

CDF
cumulative distribution function

CESM
Community Earth System Model (global climate model)

CFS
Climate/Coupled Forecast System

CFSv2
Coupled Forecast System version 2 (NOAA climate forecast model)

CHPS
Community Hydrologic Prediction System

CIMIS
California Irrigation Management Information System

CIR
crop irrigation requirement

CIRES
Cooperative Institute for Research in Environmental Sciences

CLIMAS
Climate Assessment for the Southwest

CLM
Community Land Model

CM2.1
Coupled Physical Model, version 2.1 (global climate model)

CMIP
Coupled Model Intercomparison Project (coordinated archive of global climate model output)

CNRFC
California-Nevada River Forecast Center

CoAgMET
Colorado Agricultural Meteorological Network

CoCoRaHS
Community Collaborative Rain, Hail and Snow Network

CODOS
Colorado Dust-on-Snow

CONUS
contiguous United States (the lower 48 states)

COOP
Cooperative Observer Program

CP
Central Pacific

CPC
Climate Prediction Center

CRB
Colorado River Basin

CRBPP
Colorado River Basin Pilot Project

CRPSS
Continuous Ranked Probability Skill Score

CRSM
Colorado River Simulation Model

CRSP
Colorado River Storage Project

CRSS
Colorado River Simulation System

CRWAS
Colorado River Water Availability Study
CSAS

CRWAS
Center for Snow and Avalanche Studies

CTSM
Community Terrestrial Systems Model

CU
consumptive use

CUL
consumptive uses and losses

CV
coefficient of variation

CVP/SWP
Central Valley Project/State Water Project

CWCB
Colorado Water Conservation Board

CWEST
Center for Water, Earth Science and Technology

DA
data assimilation

Daymet v.3
daily gridded surface meteorological data

DCP
Drought Contingency Plan

DEM
digital elevation model

DEOS
Delaware Environmental Observing System

DHSVM
Distributed Hydrology Soil Vegetation Model

DJF
December-January-February

DMDU
Decision Making Under Deep Uncertainty

DMI
Data Management Interface

DOD
Department of Defense

DOE
Department of Energy

DOW
Doppler [radar] on Wheels

DRI
Desert Research Institute

DTR
diurnal temperature range

EC
eddy-covariance method

EC
Environment Canada

ECCA
ensemble canonical correlation analysis

ECMWF
European Centre for Medium-Range Weather Forecasts

EDDI
Evaporative Demand Drought Index

EFAS
European Flood Awareness System

EIS
Environmental Impact Statement

En-GARD
Ensemble Generalized Analog Regression Downscaling

ENSO
El Niño-Southern Oscillation

EOF
empirical orthogonal function

EP
Eastern Pacific

ERC
energy release component

ESI
Evaporative Stress Index

ESM
coupled Earth system model

ESP
ensemble streamflow prediction

ESRL
Earth System Research Laboratory

ET
evapotranspiration

ET_0
Reference (crop) evapotranspiration

EVI
Enhanced Vegetation Index

FAA
Federal Aviation Administration

FAWN
Florida Automated Weather Network

FEWS
Famine Early Warning System

FEWS
Flood Early Warning System

FIRO
forecast-informed reservoir operations

FLOR
Forecast-oriented Low Ocean Resolution (global climate model)

FORTRAN
Formula Translation programming language

FPS
Federal Priority Streamgages

FROMUS
Forecast and Reservoir Operation Modeling Uncertainty Scoping

fSCA
fractional snow covered area

FWS
U.S. Fish and Wildlife Service

GCM
global climate model, or general circulation model

GEFS
Global Ensemble Forecast System

GEM
Global Environmental Multiscale model

GEOS
Goddard Earth Observing System (global climate model)

GeoTiff
Georeferenced Tagged Image File Format

GFDL
Geophysical Fluid Dynamics Laboratory

GFS
Global Forecast System model

GHCN
Global Historical Climatology Network

GHCN-D
Global Historical Climate Network-Daily

GHG
greenhouse gas

GIS
geographic information system

GLOFAS
Global Flood Awareness System

GLOFFIS
Global Flood Forecast Information System

GOES
Geostationary Operational Environmental Satellite

GRACE
Gravity Recovery and Climate Experiment

GRIB
gridded binary or general regularly-distributed information in binary form

gridMET
Gridded Surface Meteorological dataset

GSSHA
Gridded Surface/Subsurface Hydrologic Analysis

GW
groundwater

HCCD
Historical Canadian Climate Data

HCN
Historical Climatology Network

HDA
hydrologic data assimilation

HDSC
Hydrometeorological Design Studies Center

HEFS
Hydrologic Ensemble Forecast Service

HESP
Hierarchical Ensemble Streamflow Prediction

HL-RDHM
Hydrologic Laboratory-Research Distributed Hydrologic Model

HMT
Hydromet Testbed

HP
hydrological processor

HRRR
High Resolution Rapid Refresh (weather model)

HSS
Heidke Skill Score

HTESSEL
Land-surface Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land

HUC
Hydrologic Unit Code

HUC4
A 4-digit Hydrologic Unit Code, referring to large sub-basins (e.g., Gunnison River)

HUC12
A 12-digit Hydrologic Unit Code, referring to small watersheds

ICAR
Intermediate Complexity Atmospheric Research model

ICS
intentionally created surplus

IDW
inverse distance weighting

IFS
integrated forecast system

IHC
initial hydrologic conditions

INSTAAR
Institute of Arctic and Alpine Research

IPCC
Intergovernmental Panel on Climate Change

IPO
Interdecadal Pacific Oscillation

IRI
International Research Institute

iRON
Interactive Roaring Fork Observing Network

ISM
Index Sequential Method

JFM
January-February-March

JJA
June-July-August

K-NN
K-Nearest Neighbor

Landsat
Land Remote-Sensing Satellite (System)

LAST
Lane's Applied Stochastic Techniques

LERI
Landscape Evaporative Response Index

lidar
light detection and ranging

LOCA
Localized Constructed Analog

LSM
land surface model

M&I
municipal and industrial (water use category)

MACA
Multivariate Adaptive Constructed Analog

maf
million acre-feet

MAM
March-April-May

MEFP
Meteorological Ensemble Forecast Processor

METRIC
Mapping Evapotranspiration at high Resolution with Internalized Calibration

MJO
Madden-Julian Oscillation

MMEFS
Met-Model Ensemble Forecast System

MOCOM
Multi-Objective Complex evolution

MODDRFS
MODIS Dust Radiative Forcing in Snow

MODIS
Moderate Resolution Imaging Spectroradiometer

MODIS LST (MYD11A2)
Moderate Resolution Imaging Spectroradiometer Land Surface Temperature (MYD11A2)

MODSCAG
MODIS Snow Covered Area and Grain-size

MPR
Multiscale Parameter Regionalization

MRM
Multiple Run Management

MT-CLIM (or MTCLIM)
Mountain Climate simulator

MTOM
Mid-Term Probabilistic Operations Model

NA-CORDEX
North American Coordinated Regional Downscaling Experiment

NAM
North American Monsoon

NAO
North Atlantic Oscillation

NARCCAP
North American Regional Climate Change Assessment Program

NARR
North American Regional Reanalysis

NASA
National Aeronautics and Space Administration

NASA JPL
NASA Jet Propulsion Laboratory

NCAR
National Center for Atmospheric Research

NCCASC
North Central Climate Adaptation Science Center

NCECONET
North Carolina Environment and Climate Observing Network

NCEI
National Centers for Environmental Information

NCEP
National Centers for Environmental Prediction

nClimDiv
new Climate Divisional (NOAA climate dataset)

NDBC
National Data Buoy Center

NDVI
Normalized Difference Vegetation Index

NDWI
Normalized Difference Water Index

NEMO
Nucleus for European Modelling of the Ocean (global ocean model)

NevCan
Nevada Climate-ecohydrological Assessment Network

NGWOS
Next-Generation Water Observing System

NHMM
Bayesian Nonhomogenous Hidden Markov Model

NICENET
Nevada Integrated Climate and Evapotranspiration Network

NIDIS
National Integrated Drought Information System

NLDAS
North American Land Data Assimilation System

NMME
North American Multi-Model Ensemble

NN R1
NCEP/NCAR Reanalysis

NOAA
National Oceanic and Atmospheric Administration

NOAH
Neural Optimization Applied Hydrology

Noah-MP
Noah-Multi-parameterization Model

NOHRSC
National Operational Hydrologic Remote Sensing Center

NPP
Nonparametric paleohydrologic method

NRCS
Natural Resource Conservation Service

NSF
National Science Foundation

NSIDC
National Snow and Ice Data Center

NSMN
National Soil Moisture Network

NVDWR
Nevada Department of Water Resources

NWCC
National Water and Climate Center

NWIS
National Water Information System

NWM
National Water Model

NWP
numerical weather prediction

NWS
National Weather Service

NWSRFS
National Weather Service River Forecast System

NZI
New Zealand Index

OCN
Optimal Climate Normals

OHD
Office of Hydrologic Development

OK Mesonet
Oklahoma Mesoscale Network

ONI
Oceanic Niño Index

OWAQ
Office of Weather and Air Quality

OWP
Office of Water Prediction

PC
principal components

PCA
principal components analysis

PCR
principal components regression

PDO
Pacific Decadal Oscillation

PDSI
Palmer Drought Severity Index

PET
potential evapotranspiration

PGW
pseudo-global warming

PRISM
Parameter-elevation Relationships on Independent Slopes Model

PSD
Physical Sciences Division

QBO
Quasi-Biennial Oscillation

QDO
Quasi-Decadal Oscillation

QM
quantile mapping

QPE
Quantitative Precipitation Estimate

QPF
Quantitative Precipitation Forecast

QTE
Quantitative Temperature Estimate

QTF
Quantitative Temperature Forecast

radar
radio detection and ranging

RAP
Rapid Refresh (weather model)

RAWS
Remote Automated Weather Station Network

RCM
Regional Climate Model

RCP
Representative Concentration Pathway

RE
reduction-of-error

RFC
River Forecast Center

RFS
River Forecasting System

RH
relative humidity

RiverSMART
RiverWare Study Manager and Research Tool

RMSE
root mean squared error

S/I
seasonal to interannual

S2S
subseasonal to seasonal

Sac-SMA
Sacramento Soil Moisture Accounting Model

SAMS
Stochastic Analysis Modeling and Simulation

SCA
snow-covered area

SCAN
Soil Climate Analysis Network

SCE
Shuffled Complex Evolution

SCF
seasonal climate forecast

SE
standard error

SECURE
Science and Engineering to Comprehensively Understand and Responsibly Enhance Water

SFWMD
South Florida Water Management District

SM
soil moisture

SMA
Soil Moisture Accounting

SMAP
Soil Moisture Active Passive

SMHI
Swedish Meteorological and Hydrological Institute

SMLR
Screening Multiple Linear Regression

SMOS
Soil Moisture and Ocean Salinity

SNODAS
Snow Data Assimilation System

SNOTEL
Snow Telemetry

SOI
Southern Oscillation Index

SON
September-October-November

SPoRT
Short-term Prediction Research Transition

SRES
Special Report on Emissions Scenarios

SRP
Salt River Project

SSEBOP
Simplified Surface Energy Balance

SSEBOP ET
Simplified Surface Energy Balance Evapotranspiration

SSP
Societally Significant Pathway

SST
sea surface temperatures

SSW
stratospheric sudden warming

SubX
Subseasonal Experiment

SUMMA
Structure for Unifying Multiple Modeling Alternatives

SVD
singular value decomposition

SW
surface water

SWANN
Snow-Water Artificial Neural Network Modeling System

SWcasts
Southwest Forecasts

SWE
snow water equivalent

SWOT
Surface Water and Ocean Topography

SWS
Statistical Water Supply

Tair
air temperature

Tdew
dew point temperature

TopoWx
Topography Weather (climate dataset)

TVA
Tennessee Valley Authority

UC
Upper Colorado Region (Reclamation)

UCAR
University Corporation for Atmospheric Research

UCBOR
Upper Colorado Bureau of Reclamation

UCRB
Upper Colorado River Basin

UCRC
Upper Colorado River Commission

UCRSFIG
Upper Colorado Region State-Federal Interagency Group

USACE
U.S. Army Corps of Engineers

USBR
U.S. Bureau of Reclamation

USCRN
U.S. Climate Reference Network

USDA
U.S. Department of Agriculture

USGCRP
U.S. Global Change Research Program

USGS
U.S. Geological Survey

USHCN
United States Historical Climatology Network

VIC
Variable Infiltration Capacity (model)

VIIRS
Visible Infrared Imaging Radiometer Suite

VPD
vapor pressure deficit

WBAN
Weather Bureau Army Navy

WCRP
World Climate Research Program

WFO
Weather Forecast Office

WPC
Weather Prediction Center

WRCC
Western Regional Climate Center

WRF
Weather Research and Forecasting

WRF-Hydro
WRF coupled with additional models to represent hydrologic processes

WSF
water supply forecast

WSWC
Western States Water Council

WUCA
Water Utility Climate Alliance

WWA
Western Water Assessment

WWCRA
West-Wide Climate Risk Assessments

WWMPP
Wyoming Weather Modification Pilot Project


WESTERN WATER ASSESSMENT
A NOAA RISA TEAM
CIRES
University of Colorado Boulder