Colorado River Basin Climate and Hydrology

State of the Science

April 2020

Western Water Assessment

Chapter 1

Introduction

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

CIRES

University of Colorado Boulder

Colorado River Basin Climate and Hydrology
State of the Science

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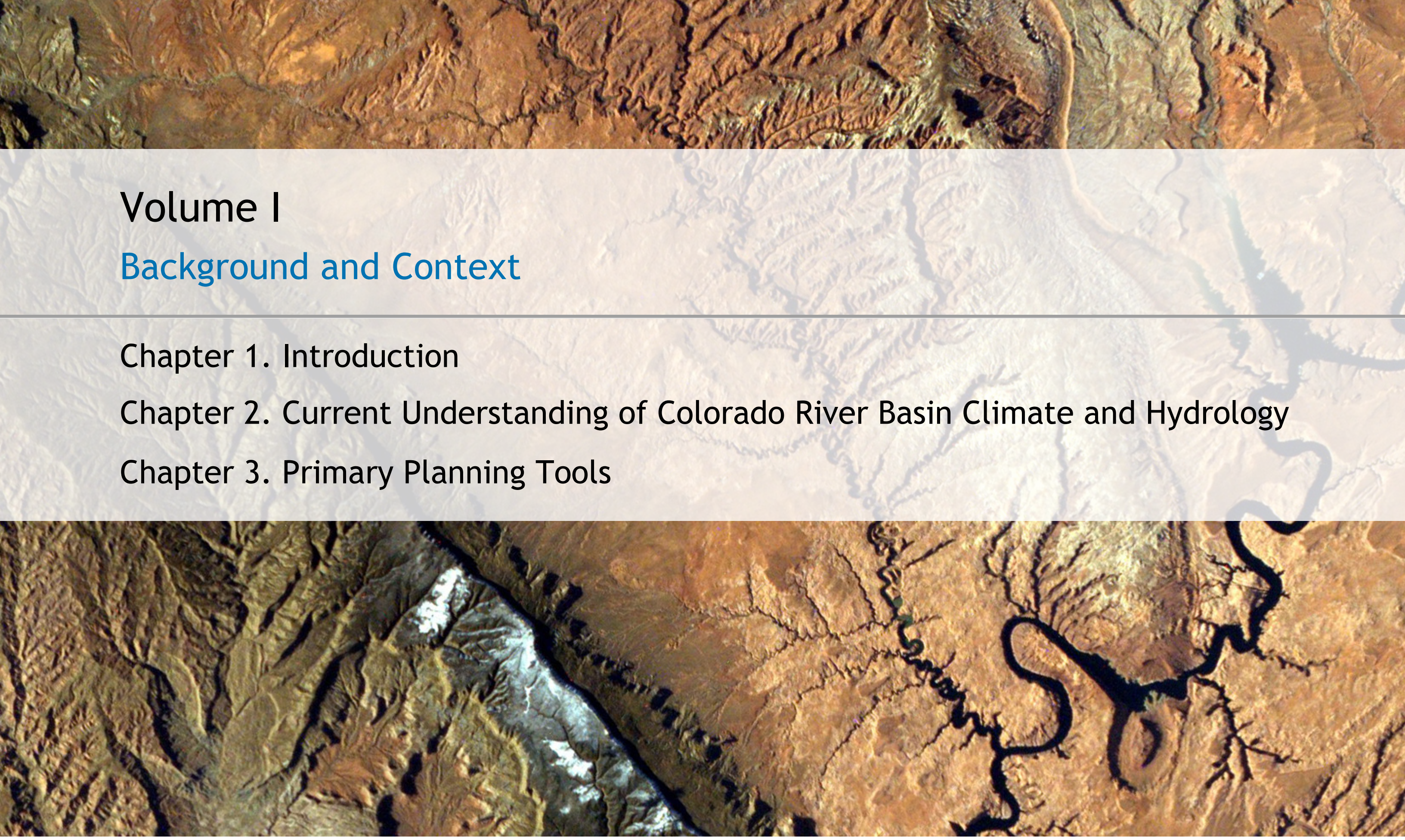

Volume I

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 1
Introduction

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1.1 Background and need

The Colorado River Basin is a vital source of water, ecosystem services, hydropower, recreation, and other amenities for the seven basin states (Colorado, Wyoming, Utah, New Mexico, Arizona, Nevada, and California), at least 22 federally recognized tribes, and the Republic of Mexico (Figure 1.1). The Colorado River system is managed and operated in accordance with the Law of the River, which consists of compacts, treaties, federal laws, regulations, contracts, and court decisions and decrees.

Law of the River
See Reclamation's website for links to many of the relevant documents.

Link: https://www.usbr.gov/lc/region/pao/lawofrvr.html

There is an increasing imbalance between supply and demand in the basin. Water use, including consumptive use, within the basin has steadily increased over time and, when combined with deliveries to Mexico, is now approaching the average historical water supply (Figure 1.2). The average conditions, over time and across the basin, suggest a (barely) sufficient supply and, by smoothing out the variability, mask existing and prospective shortages.

Since 2000, the basin has experienced an extended dry period in which the average annual water supply has been 18% lower than the historical average. The enormous storage capacity of the system's reservoirs (about 60 million acre-feet), nearly full at the beginning of the dry period, combined with voluntary conservation has permitted full deliveries of water to the Lower Basin states through this period, with only local shortages to uses in Upper Basin states. But the cumulative streamflow deficit of about 40 million acre-feet (maf) since 2000 has contributed to the depletion of system storage to about 45% of capacity.

The depleted state of system reservoirs leaves the system vulnerable; the water surface elevation of Lake Mead has hovered around the upper thresholds (1075' and 1090') for imposing curtailments on Lower Basin states under the 2007 Interim Guidelines and the 2019 Drought Contingency Plan.

This recent drought, along with the increasing recognition that rising temperatures impact the hydrology of the basin, has led to further concerns about the long-term reliability of basin water supplies. Warming temperatures observed across the basin in the last few decades have discernibly impacted snowpacks, melt and runoff timing, runoff efficiency, and total basin runoff. It is unclear whether the period of below-normal precipitation since 2000 is indicative of future precipitation, but unless average basin precipitation increases substantially, system runoff and water supply are expected to decline over the next several decades due to warming alone.

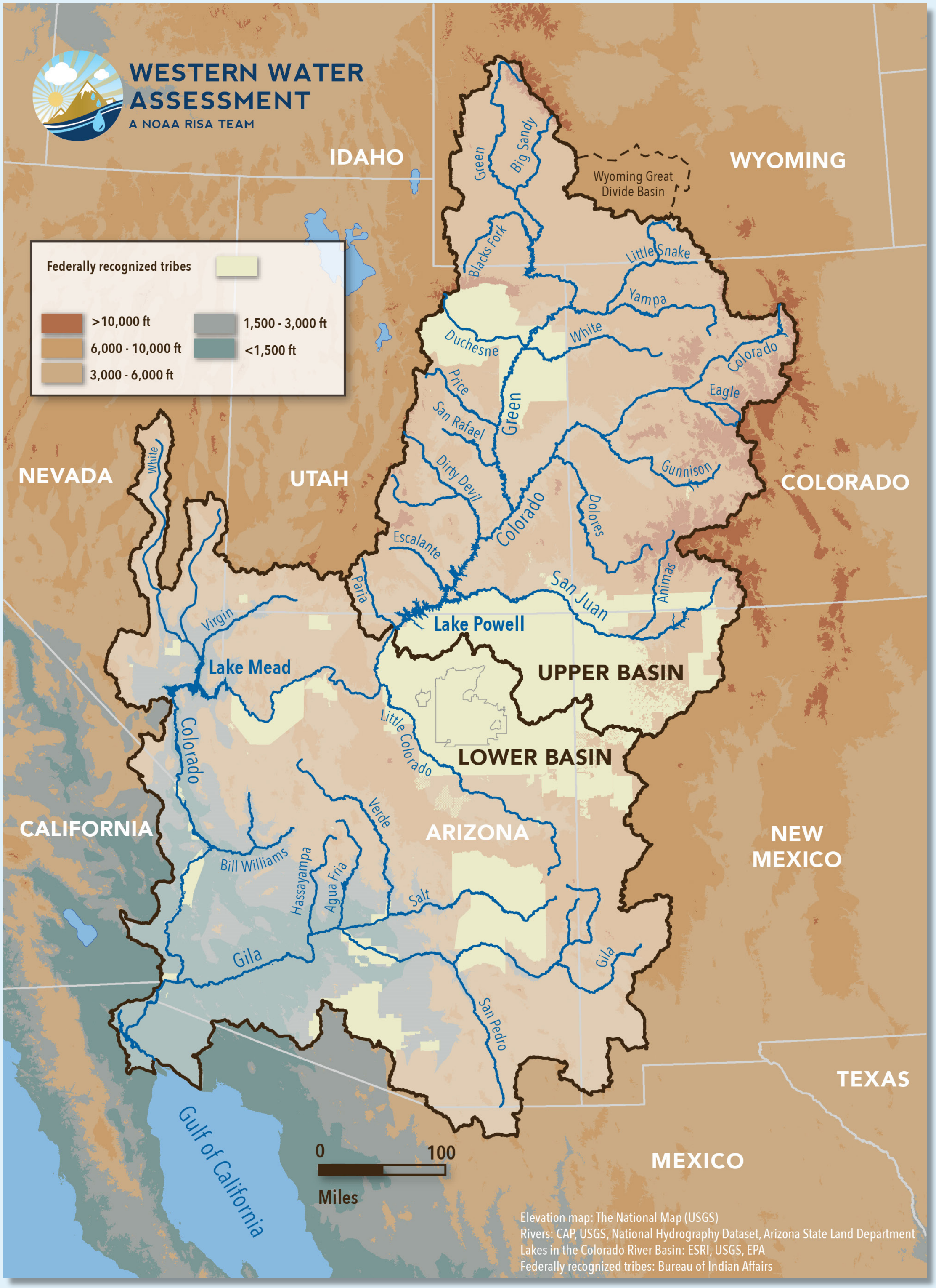

Figure 1.1

Geographic setting of the Colorado River Basin. Upper Basin: portions of the basin that lie in Colorado, Utah, Wyoming, New Mexico, and Arizona that are tributary to the river upstream of the Colorado River Compact point at Lee Ferry, Arizona. Lower Basin: portions of the basin in Arizona, California, Nevada, and New Mexico that are downstream of Lee Ferry.

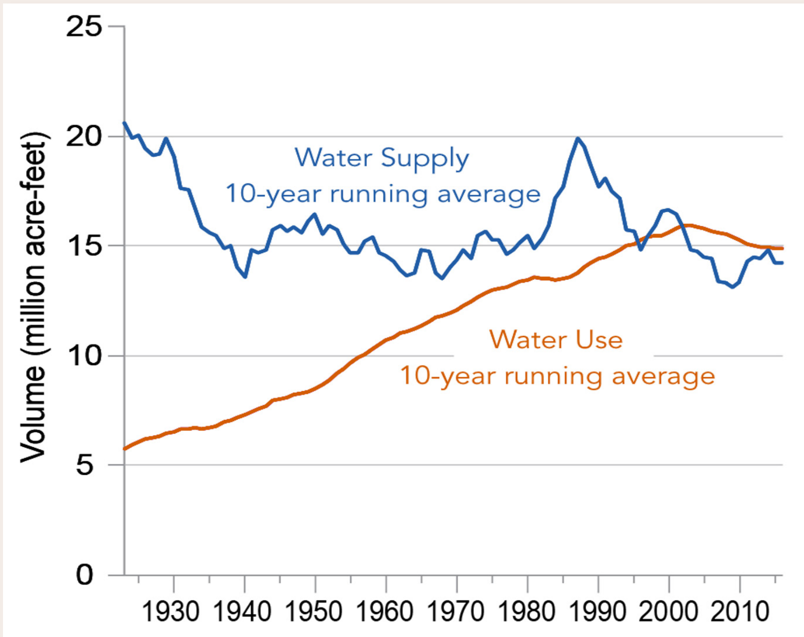

Figure 1.2
Historical water supply and consumptive water use for the Colorado River Basin, as aggregated at Imperial Dam, from 1922 to 2016, smoothed with a 10-year running average. Since 2000, water use has exceeded water supply on a 10-year basis, as well as in most individual years. (Source: USGCRP 2018, revised from Reclamation 2012e)

Water resource managers in the basin have long relied on short-term (1 month to 2 years) forecasts of system conditions to guide operations and other decision making. Recently, the U.S. Bureau of Reclamation (hereinafter "Reclamation") has instituted mid-term probabilistic forecasts (2 to 5 years) to bridge short-term forecasts with longer-term planning projections. When the system is close to critical operational thresholds, such as the 1075' and 1090' levels in Lake Mead, the need for accurate and actionable short-to-mid-term forecasts of system conditions becomes even more critical.

Until recently, long-term water planning (5 to 50 years) in the basin was based on the historical hydrologic record under the assumption of hydroclimatic stationarity, that is, that the historical average and variability would remain stable. That assumption was first challenged several decades ago by tree-ring records showing the instability of century-scale hydroclimate in the basin, and has become even less tenable due to climate change (Milly et al. 2008; 2015). When developing the 2007 Interim Guidelines, Reclamation, recognizing the limitations of the conventional assumption of stationarity, used tree-ring reconstructed, pre-historic flows to provide a broader view of flow variability (Reclamation 2007b), and also surveyed the state of knowledge regarding the potential impact of climate change on water resources in the basin (Reclamation 2007c). Since that time, climate model projections have played larger roles in informing the hydrologic traces in Reclamation planning studies (Reclamation 2012e). Reclamation's experience, and that of other water agencies working with climate model data, has revealed considerable challenges in both translating global climate projections to changes in the hydrology of the Colorado River Basin and in interpreting the system impacts associated with those changes given the uncertainties in the data and models.

The past decade has seen dozens of new research efforts aimed at better understanding the climate and hydrology of the Colorado River Basin, and at refining the data and models used to guide basin management and planning. There have been parallel efforts to explore new approaches to planning and decision making under uncertainty. Many of these efforts have been conducted by, or with funding from, Reclamation and other basin water agencies. Many other research studies, while not explicitly guided by the needs of basin water managers, can still provide relevant information and insight. Given this rapidly expanding scientific knowledge base, the increasing complexity of the data and models used to operationalize that knowledge, and the growing uncertainties about the hydroclimatic future, basin stakeholders have recognized the importance of reassessing the scientific and technical basis for management and planning. The impending formal review of the 2007 Interim Guidelines, which must begin in 2020 (U.S. Secretary of the Interior 2007), and the potential renegotiation of those guidelines, has created additional impetus for such a reassessment.

In May, 2017, the Southern Nevada Water Authority hosted a conference, the Colorado River Hydrology Research Symposium (Cawthorne 2017), to give water resource practitioners and researchers an opportunity to exchange information about operational practices and research initiatives, with a focus on opportunities to improve inputs to existing basin planning tools and to enhance the utility of those tools. One outcome of that symposium was recognition that a document that synthesized the current research and assessed it in the context of the primary planning processes was necessary.

1.2 Objectives and approach

The intention of this report is to assess scientific knowledge and technical practice in a systematic way, across the multiple timescales and the diverse data and models used to inform management and planning in the basin. It describes the concepts, methods, models, and datasets that currently contribute to Reclamation's and other stakeholders' operations and planning, as well as knowledge gaps, uncertainties, and future challenges and opportunities. No new research or quantitative analyses were performed for this report beyond the basic characterization of existing datasets.

Objectives

By synthesizing the state of the science in the Colorado River Basin regarding climate and hydrology, the report seeks to establish a broadly shared understanding that can guide the strategic integration of new research into practice. The ultimate goal of that integration, and therefore of this report, is to facilitate more accurate short- and mid-term forecasts, and more meaningful long-term projections, of basin hydroclimate and system conditions.

The specific objectives of this report include the following:

- Synthesize recent findings that can inform forecasts (short-term and mid-term) and projections (long-term) of hydroclimate and system conditions.
- Convey the knowledge gaps and uncertainties associated with each area of the science and technical practice, as well as with key datasets and models.
- Prompt research ideas and inform research priorities by describing opportunities for closing knowledge gaps.
- Inform the scientific community about Reclamation models, how they support operations and planning, and related research needs.
- Provide a broadly accepted foundation of scientific and technical issues on which to enter the formal review and potential renegotiation of the Interim Guidelines.

Sources

This report draws from over 700 primary sources, mainly peer-reviewed research articles published in academic journals, as well as agency studies, reports, analyses, and other sources. It builds on prior planning studies, research syntheses, and information needs assessments that have focused on the Colorado River Basin and water resources management that are listed in Table 1.1.

Audience

This report was written to be a clear and useful reference for readers who come to it with a moderate level of scientific and technical understanding of hydrology, though much of the text is fully accessible to any reader. The audience for the report includes water resource engineers and analysts who routinely work with inputs to, or outputs from, Reclamation models or who otherwise engage with water operations and planning in the basin; decision makers who will prescribe changes to operations, plans, and policies, and could benefit from better understanding of the science that informs these activities; research program managers seeking insights on high impact priorities to promote; and researchers who could benefit from better understanding of the planning and decision context in the basin. The report is also intended to inform the funding and production of research that effectively supports basin water management activities, and is therefore also aimed at the broader community of water interests in the basin.

Table 1.1

Planning studies, research syntheses, and information needs assessments referenced in this report.

Document	Year	Geographic scope	Reference
Planning studies conducted by Reclamation or basin stakeholders			
Final EIS—Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead, Appendices N and U	2007	Colorado River Basin	Reclamation (2007b; 2007c)
Colorado River Basin Supply and Demand Study	2012	Colorado River Basin	Reclamation (2012e)
Colorado River Water Availability Study	2012	Major Colorado River tributary basins within the state of Colorado	Colorado Water Conservation Board (2012)
SECURE Water Act report	2016	Western U.S.	Reclamation (2016)
Colorado River Basin Ten Tribes Partnership Tribal Water Study	2018	Colorado River Basin	Reclamation (2018)
Climate change assessments that cover part or all of the Colorado River Basin			
Climate Change in Colorado	2008	Colorado	Ray et al. (2008)
Joint Front Range Climate Change Vulnerability Study	2012	Colorado	Woodbury et al. (2012)
Assessment of Climate Change in the Southwest United States	2013	Southwestern U.S.	Garfin et al. (2013)
Climate Change in Colorado	2014	Colorado	Lukas et al. (2014)
Fourth National Climate Assessment, Volume I	2017	U.S.	US Global Change Research Program (2017)
Fourth National Climate Assessment, Volume II, Chapter 25	2018	Southwestern U.S.	Gonzalez et al. (2018)
Stakeholder needs assessments for climate information			
Options for Improving Climate Modeling to Assist Water Utility Planning for Climate Change	2009	U.S.	Barsugli et al. (2009)
Addressing Climate Change in Long-Term Water Resources Planning and Management: User Needs for Improving Tools and Information	2011	U.S.	Brekke (2011)
Short-Term Water Management Decisions: User Needs for Improved Climate, Weather, and Hydrologic Information	2013	U.S.	Raff et al. (2013)

1.3 Organization

The organization of the report centers on the three main Reclamation operations and planning models for the basin and the respective timescales those models are designed to inform. The models are:

- 24-Month Study Model (24MS)—short term (current month to 24 to 36 months in the future)
- Mid-Term Probabilistic Operations Model (MTOM)—mid-term (current month to 2 to 5 years in the future)
- Colorado River Simulation System (CRSS)—long term (5 to 50 years)

In general, operational and planning decisions by Reclamation or basin stakeholders use information from the four categories of models or data listed below.

I. **System Models.** The three primary Reclamation models listed above, and equivalent models built and used by other organizations. They use as inputs the data from categories III and IV, and are also calibrated with data from category II.

II. **Primary data and models.** Observations, estimates, or simulations of climate and hydrologic conditions that are relevant across all time scales. They are used to calibrate, provide inputs to, and validate models and analyses in categories I, III, and IV.

III. **Short- and mid-term forecast tools.** Models and methods for forecasting weather, climate, and streamflow as the basis for short-to-mid-term operations.

IV. **Long-term planning hydrology.** Data and models (historically-based, paleo-reconstructed, and climate change-informed) used to represent past and current variability, and to project long-term future conditions for planning purposes.

This report is organized into four volumes (I–IV) corresponding to these categories, reflecting the flow of information through the chain of models and data. While that flow actually culminates with the Reclamation system models, those models are described early in the report (Volume I, Chapter 3) to set the stage for consideration of the manifold inputs to those models.

In Chapters 3 through 11, the text describes the following for each type of model or data:

- Importance to the chain of models and data, and thus to basin operations and planning
- The specific data and methods currently used in the Reclamation models, and how they compare with other data and methods
- Recent or ongoing efforts at improvement in this area
- Key challenges, knowledge gaps, and uncertainties that remain
- Opportunities for further progress

1.4 Topics beyond the scope of this report

This report does not evaluate current basin operations and policy or provide recommendations. It also does not address ecosystem processes except as they affect water supply, nor does it cover water quality concerns in any detail.

Water use is obviously a critical component of the system water balance in the Colorado River Basin. Specific aspects of water use are briefly addressed in this report: the representation of consumptive water uses and losses in the Reclamation system models (Chapter 3); methods for measuring and monitoring water uses and losses (Chapter 5); and the effects of climate change on consumptive use (Chapter 11). Other sections may include discussions of data, tools, and concepts that, while oriented toward water supply, are relevant to the quantification of current consumptive uses and losses and the forecasting of future water demand. But a comprehensive treatment of the scientific and technical issues surrounding water use in the basin is beyond the scope of this report. The state of monitoring and forecasting water use in the basin for planning purposes is described in Technical Report C of the Colorado River Basin Water Supply and Demand Study (Reclamation 2012d).

SPOTLIGHT

Sources of uncertainty in modeling natural systems

The uncertainties in hydroclimate forecasts and projections, and therefore in water supply expectations, present tantalizing research questions for scientists but are a source of frustration for water resource practitioners charged with providing a reliable water supply. Given the stakes involved, it is reasonable that Colorado River Basin planners and managers desire greater certainty in water supply forecasts and long-term projections; they need some sense of the likelihood of hydrologic shifts, especially shifts to the dry side.

Uncertainty stems from either randomness in the behavior of the system being modeled (aleatory uncertainty) or incomplete knowledge of the system (epistemic uncertainty). The aleatory uncertainty in hydroclimate processes is effectively synonymous with natural variability and, as such, can't be reduced by more research or computing power or data collection. Just as we cannot buy down the uncertainty in a coin flip, we cannot buy down aleatory uncertainty in hydroclimate processes. However, aleatory uncertainty as manifested in variability is an intrinsic element of hydrologic systems, so its conceptual and practical nature is well understood by water resource managers and stakeholders.

Epistemic uncertainty, on the other hand, can be chipped away at by improving our understanding, computing power, and data collection. There is epistemic uncertainty about aleatory uncertainty (variability) which frequently will be reduced simply by making more observations. For example, the exceptional nature of the wet period at the beginning of the 20th century was revealed over time as the observed records of precipitation and streamflow became longer. There are several general types of epistemic uncertainty in modeling natural systems, illustrated in Figure 1.3 and described below:

- **Conceptual**. Uncertainty that comes from incomplete understanding of the system to be modeled, so that relevant variables and processes are not represented in the model or the underlying dependencies between and among processes and variables is poorly understood.
- **Structural**. Uncertainty that comes from inadequate specification of the underlying physics and other physical relationships in the model, or the imperfect fit of a statistical model. Approximation or simplification of processes over time and space is another source of structural uncertainty.
- **Parameter**. Uncertainty that comes from errors in specifying model parameters—usually these are fixed coefficients or terms based on observations. Aggregation or simplification of inputs over time and space is another source of parameter uncertainty.
- **Data**. Uncertainty that arises from limitations in observing systems and measurement techniques. Data uncertainty is fundamental because it confounds our conceptual and quantitative understanding of natural systems. Calibration of model parameters against imperfect data contributes to parameter uncertainty.
- **Initial conditions**. Uncertainty that comes from imperfectly capturing the state of the system that begins a model simulation; it includes measurement error, and even more so, uncertainties related to the spatial and temporal interpolation between observations.

Uncertainties accumulate such that the combined uncertainty in the ultimate planning model output is much larger than the uncertainty at any intermediate step; however, because of interdependencies, the combined uncertainty isn't a simple addition. Ultimately, depending on the variable and time scale of interest, the combined epistemic uncertainties may be matched or exceeded by that stemming from the natural variability of the Colorado River Basin.

This report summarizes the current understanding in the research community about the uncertainties in hydroclimate analyses. However, the full range of uncertainty in future system outcomes, as it applies to the Colorado River Basin, also includes future land use, future water demand, and the future state of institutions, economies, technologies, and policies that influence and constrain water demand and allocation. Water resource practitioners in the basin are trying to make the best decisions possible about infrastructure, operations, and demand management given the uncertainty in future water supply. Studies to support decision making in this new environment are beginning to explore alternative analytical approaches that address the lack of information about the future by first evaluating system sensitivities, vulnerabilities, or failure modes. This emerging paradigm is reflected in the "decision making under deep uncertainty" (DMDU) movement. DMDU often uses computationally intensive methods, testing a system's vulnerability to a range of possible futures under multiple policy options, to formulate robust decisions. It is possible that approaches to decision making such as these may be more likely to benefit management and planning than efforts to reduce some of the epistemic uncertainties, but discussion and evaluation of the approaches and the trade-offs is beyond the scope of this report.

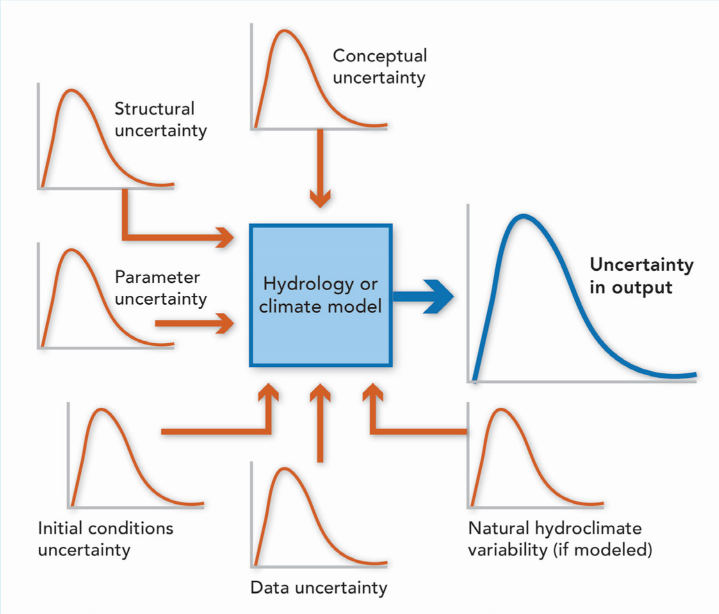

Figure 1.3
Sources of uncertainty in modeling natural systems. The figure shows hypothetical probability density functions combining to representing the overall uncertainty in model output.

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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