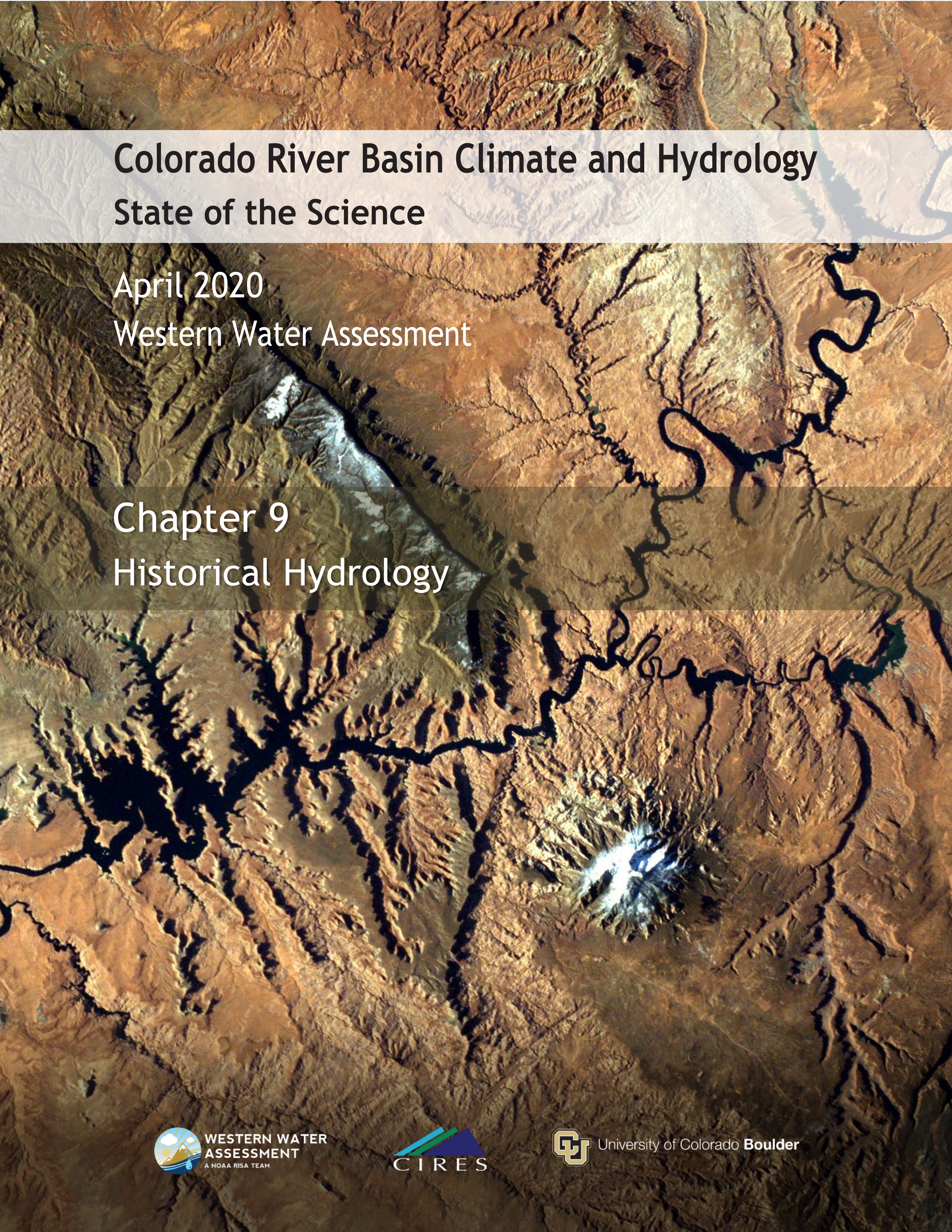

Colorado River Basin Climate and Hydrology

State of the Science

April 2020

Western Water Assessment

Chapter 9

Historical Hydrology

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 IV

Long-term—Informing the 5-Year to 50-Year Time Horizon

Chapter 9. Historical Hydrology

Chapter 10. Paleohydrology

Chapter 11. Climate Change-Informed Hydrology

Volume IV of the Colorado River Basin State of the Science report focuses on models and methods for developing hydrologic traces that represent plausible hydrologic futures and can be run through system or planning models to evaluate the potential for outcomes and impacts of interest over the next 5 to 50 years. The three main approaches for developing such traces are Historical Hydrology (Chapter 9), Paleohydrology (Chapter 10), and Climate Change-informed Hydrology (Chapter 11). Long-term hydrologies generated using one or more of these approaches are used as driving inputs for Reclamation's CRSS planning model, as well as similar planning and system models used by other organizations. The three chapters in Volume IV provide comprehensive descriptions and assessments of the respective approaches and their variants, the data they require, their applications, and their tradeoffs. It is important to examine and understand these choices in order to select appropriate hydrologic traces for system modeling and risk, and also to interpret the output of system modeling that has already been performed.

Traditional long-term planning methods are based on the assumption that future hydrology will have characteristics (average, variance, extremes) similar to the historical observed hydrology. The extreme hydrologic drought of 2000–2004, unprecedented in the observed record, highlighted the downside of basing expectations for future hydrology only on the observed record (i.e. historical hydrology). Clearly, hydrologic behavior outside the range of the past 100 years was, and is, possible. Accordingly, the system analyses performed by Reclamation to support the 2007 Interim Guidelines included, for the first time, ensembles of hydrologic traces based on tree-ring reconstructions of basin paleohydrology. These traces show a broader range of natural variability, including more severe and sustained droughts, than those based only on the past century's observed hydrology (Chapter 2).

As the dry period that began in 2000 persisted, studies modeling the future impacts of human-caused climate change on basin hydrology consistently indicated that the 21st century was likely to see systematic shifts in hydrologic conditions: earlier snowmelt and runoff, lower runoff efficiency, and (with less certainty) a decline in annual streamflow. Because Reclamation and other basin stakeholders saw the need to explicitly represent this additional climate change risk in planning studies, Appendix U in the 2007 Interim Guidelines laid out a pathway for developing and using climate change-informed hydrologic traces. In 2012, the Basin Study formally incorporated a climate change-informed ensemble along with traces based on historical hydrology and paleohydrology, using Robust Decision Making techniques to assess risks from all scenarios on an equal footing.

As with the historical hydrology and paleohydrology, a typical analysis of climate change-informed hydrology will outline an ensemble of potential future trajectories for basin hydrology. Over longer planning horizons (30 years or more), the range depicted by this ensemble is even broader than those depicted by historical hydrology and paleohydrology, most notably on the dry side of the distribution.

Several planning studies for the basin have used hydrologic traces that effectively blend information from two or more types of hydrology; these are described in greater detail within the listed chapters:

- "Paleo-conditioned" hydrology takes state-transition (wet-dry) information and resamples the historical hydrology to create new sequences that reflect paleo-variability (Chapter 10)
- Delta-method statistical downscaling takes future change factors in temperature and precipitation from climate-model ensembles and perturbs the historical climate sequence to simulate the historical hydrologic variability recurring under future climate (Chapter 11)
- Temperature-perturbed hydrology is similar to the above, but uses several prescribed temperature change factors to simulate the historical hydrologic variability recurring under a warmer climate, assuming no precipitation changes (Chapter 11)

While the sequence of the three chapters may suggest an evolution or transition, it would be incorrect to conclude that climate change-informed hydrology is now the preferred or optimal source of long-term traces to drive system models for planning studies. All three main sources of hydrologic ensembles (historical, paleohydrology, climate change-informed) have inherent advantages and limitations, summarized in the table below. These attributes may be more or less relevant depending on the time horizon of a risk assessment. For example, assessing risk five years into the future would not need to account for the sources of future uncertainty that longer-term studies must grapple with. For long-term risk assessments, it is more helpful to base analyses on at least two, and ideally all three types of hydrology, than any single type; more specifically, it is inappropriate to assume the historical hydrology will repeat itself. To further reduce the impacts of the assumptions inherent to any ensemble, it may be beneficial to use advanced analytical and decision-support frameworks that deemphasize probabilistic risk.

Key characteristics of the main types of hydrology, observed, paleohydrology, and climate change-informed. (Source: adapted from Lukas et al. 2014)

	Historical hydrology (Chapter 9)	Paleohydrology (Chapter 10)	Climate change-informed hydrology (Chapter 11)
Most useful information to extract from this type of hydrology	Variability (interannual to decadal); recent trends	Variability (interannual to multi-decadal); shifts in mean and variability	Potential long-term future changes
Embedded assumption in using this to inform planning	Historical mean and variability is stable over time and is representative of future risk	Pre-1900 hydrology, including severe droughts and shifts in mean and variability, can recur in the future	Climate models can provide reliable information about future changes in the basin
Key data and models	Gaged observations of streamflow and major diversions; water-balance model to naturalize streamflow (except at headwaters gages)	Tree-ring chronologies (site time-series); statistical models relating ring-width to climate and hydrology	Global climate models, statistical downscaling and bias-correction methods; gridded climate data; regional climate models; hydrology models
Advantages	Provides baseline information about risk; relates other sources of information to our experience of system impacts; readily available, trusted, and well-vetted	Shows broader range of natural variability than seen in the observed records; places observed variability in longer context; provides many sequences of wet and dry years	Best source of information about potential effects of future climate change on hydrology
Limitations	Does not capture the full range of natural variability; does not reflect risk from future climate change; likely to underestimate future system stresses	Uncertainty in the proxy information; does not reflect risk from future climate change, though the broader range of variability may approximate that risk	Larger uncertainties in future changes, requiring consideration of many traces; complex datasets that are difficult to obtain, analyze and interpret
Primary sources of uncertainty affecting the output	Imperfect record of streamflows; inadequate characterization of depletions when naturalizing gage records	Tree rings imperfectly reflect hydroclimatic conditions; choices in handling of the tree-ring data and the model that relates tree-ring data to observed streamflows	Future emissions of greenhouse gases; differing climate models; choice of downscaling and bias-correction methods; differing hydrologic models

Chapter 9

Historical Hydrology

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Key points

- The observed historical streamflow record is used to generate ensembles of streamflow traces for input into system models for long-range planning, as well as to validate and calibrate paleohydrology and climate changed-informed hydrology.
- Multiple methods have been used to generate Colorado River Basin streamflow traces for system analysis; each has advantages and limitations and none is a clear best choice for all applications.
- The index sequential method (ISM), which has been the most common method used in Reclamation system analyses for decades, has advantages but also significant limitations, most of which center on the fact that ISM traces do not deviate from the observed historical record.
- Stochastic alternatives to ISM have been used to produce ensembles of traces that maintain many characteristics of the historical record while offering novel ranges, durations, and frequencies of flows.
- Stochastic methods that are based on statistical summaries of the historical data, known as parametric methods, have the advantage of being able to generate values beyond the range of the observed record, but require assumptions about the underlying form of the population of streamflows.
- Stochastic methods that are based on sampling directly from the historical data, known as nonparametric methods, do not require assumptions about the underlying form of the population of streamflows but are sensitive to the number of observations from which to sample.
- Research trends are toward nonparametric methods of streamflow generation and toward hybrid methods that use historical hydrology with reconstructed tree-ring hydrology or climate change-informed hydrology.

9.1 Introduction

All long-term system planning studies in the Colorado River Basin use the observed historical streamflow record, naturalized as described in Chapter 5, in one way or another. For several decades, the historical record has been used directly to generate streamflow traces for input to Reclamation's long-term planning models. The evolution of methods that use the historical record directly and the current state of long-term synthetic streamflow based on historical hydrology are described in this chapter. Methods that use the historical record to calibrate, validate, and synthesize paleohydrologic and climate change-informed streamflow traces are described in Chapters 10 and 11, respectively.

Concerns have been raised for decades that the historical record may not adequately represent long-term future hydrologic risk (Tipton and Kalmbach 1965). The full record of naturalized streamflows, which currently spans 1906 to 2018, is considered particularly problematic because it includes an extraordinary period of high flows in the early 20th century (Chapters 2 and 5). The full record also has limited representation of prolonged droughts, which research indicate have been more common in the distant past and could become more common in light of climate change (Chapter 10).

Historical hydrology is useful as a baseline to provide context for future risk; however, as conditions increasingly deviate from the observed past, there is less confidence in studies that use historical hydrology alone (Naghettini 2016). According to Vogel (2017),

> "Due to the now widespread acceptance that hydrologic systems often have and will undergo significant change, it is no longer reasonable to plan our future water resource systems by assuming that future conditions will replicate past hydrologic experience."

These concerns carry through to any system model streamflow inputs generated purely from the full observed record, but as this chapter will describe, some methods are more constrained by characteristics of the observed hydrology than others.

This chapter uses terminology that may be unfamiliar to some readers. Four terms in particular, *parametric*, *nonparametric*, *stochastic*, and *deterministic*, warrant definition up front. Figure 9.1 helps illustrate the explanations provided here. It contains a histogram with bins of annual natural flows at Lees Ferry from 1906–2016 along the x-axis and the frequency of occurrence of the flows in each bin on the y-axis. The curves on the figure are continuous theoretical probability density functions (PDFs) fit to the empirical data. Each function, or equation, provides the probable frequency of any value of annual streamflow, and is made particular to this set of observations by *parameters*, such as mean and standard deviation, which identify the location and scale of the distribution, respectively.

The green line on Figure 9.1 is the "normal" PDF. Normal PDFs are also known as bell curves because they are symmetrical on either side of the mean of the data. The normal curve is estimated from two parameters, mean and standard deviation, calculated from the observed data. Another distribution, the Johnson SB distribution, shown in blue on the figure, uses two additional parameters, skew (symmetry) and kurtosis (how quickly the tails approach zero), also calculated from the observations, to further refine the distribution. Of 50 theoretical distributions tested on this set of annual flows at Lees Ferry, the Johnson SB distribution has the best fit to the observed data, but it is not a distribution typically used in streamflow synthesis. The lognormal distribution, which can use either 2 or 3 parameters (mean and standard deviation, plus or minus skew), is shown on the figure to illustrate the discussion about parametric stochastic methods later in this chapter. The lognormal distribution, though it may not always be the best fit distribution, is often used in hydrologic studies.

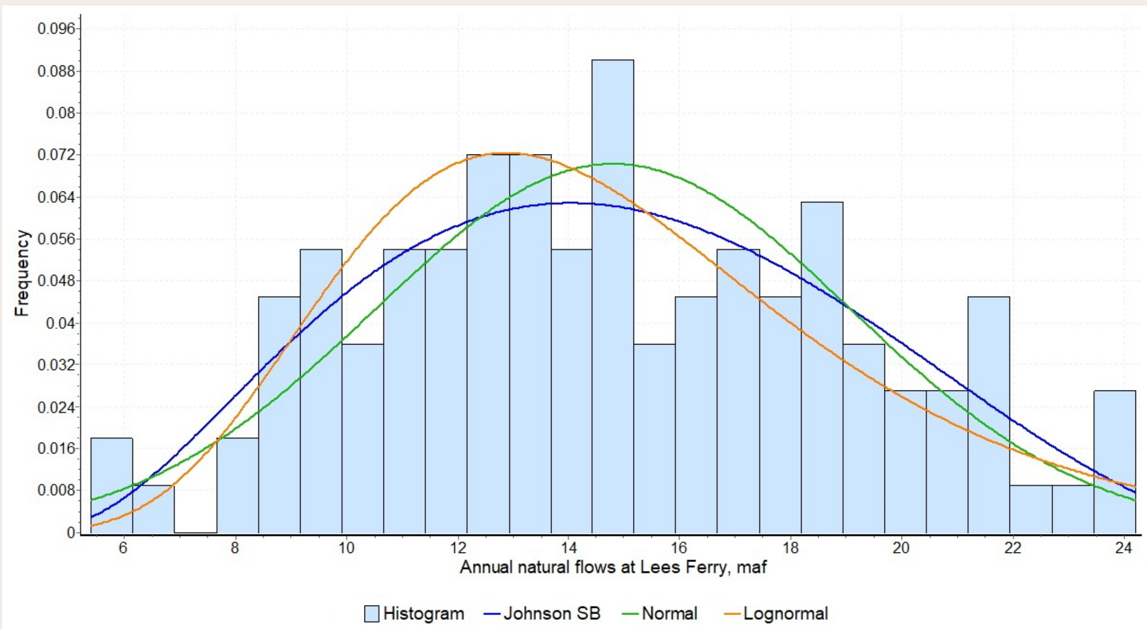

Figure 9.1

Probability density function of annual natural flows at Lees Ferry (1906–2016), in million acre-feet. (Data: Reclamation. Figure generated with EasyFit by MathWave.)

Approaches to synthetic streamflow generation that use the PDF as their basis, and therefore rely on parameters derived from the observed data, are called *parametric* approaches. These approaches are considered parsimonious because they rely on a summary of the observations, rather than the set of observations themselves (Scott 2015). Approaches that use the observed data directly, without relying on an estimated, parametric PDF, are called *nonparametric* approaches.

Parametric approaches have the advantage that they can be used when only a short record is available, or when observations at the extremes are few or non-existent, whereas nonparametric methods use the data at hand and are thus limited by the range of observations, though this limitation has been addressed in some nonparametric methods (Loucks and van Beek

2017). Nonparametric methods have the advantage of not requiring any information or assumptions or about the underlying probability distribution, and therefore are able to reflect processes that might not be represented by an assumed distribution.

Stochastic approaches to synthetic streamflow generation explicitly include uncertainty by incorporating a random component in the generation process. In stochastic approaches, the same set of inputs will result in different outputs. *Deterministic* approaches do not have a random component—the outputs are fully determined by the inputs. Stochastic approaches have the advantage of producing novel combinations of streamflow events and durations. Deterministic approaches, on the other hand, are useful when including streamflow uncertainty would be detrimental to an analysis, for example, while other, non-hydrologic variables are being tested.

9.2 Index Sequential Method

The Index Sequential Method (ISM) is a nonparametric, deterministic approach used to generate multiple streamflow time series directly from the historical, natural flow record. It was first applied by Reclamation 50 years ago to add variability to the observed hydrologic record, though the label "Index Sequential Method" was attached to the method sometime later (Reclamation 1969; Cowan, Cheney, and Addiego 1981). ISM is the method most often used in Reclamation's risk analyses.

Typically, ISM traces are sampled blocks of data from the full, historical natural flow record. The 1906-2017 record is used in examples in this chapter, but Reclamation has updated the record to 2018. The trace lengths correspond to the planning horizon under study. For example, a modeling study for years 2020 to 2060 would use traces that were 41 years long. The number of unique traces that can be generated from the record with ISM equals the number of years in the record (112 traces from the 1906-2017 record). The steps in generating ISM traces are described in the next paragraph and illustrated in Figure 9.2.

Using ISM, the first generated trace (Trace 1 in Figure 9.2) is equivalent to the historical record, beginning at the record's first year (usually 1906 but can be other years depending on the study goals) and ending with the year corresponding to the desired trace length. For each additional trace, the start year is advanced by one year and one year of historical data is picked up at the end of the trace (Traces 2–72). Each additional trace steps forward and eventually reaches the end of the full natural flow record (Trace 72).

When the end of the natural flow record is reached before the end of the planning horizon, the start year of the natural flow record is repeated by appending it to the end (Trace 73). This wrapping is repeated for each additional trace, with the start year advanced by one year and another year from the beginning of the natural flow record wrapped back to the end, until the desired number of sequences is obtained or the original, historical ordering reoccurs.

With ISM, the historical, year-to-year streamflow sequence is preserved in each trace except when wrapping occurs. Following the steps described above for traces that contain wrapping (Traces 73–112), a junction between the original end year and the original start year is introduced, as in Trace 73, creating an ordering of flows not seen in the historical record. Traces generated by ISM are therefore sensitive to the chosen start year—wrapping that year's natural flow to the end of a trace can impact whether hydrologic conditions rebound, stay about the same, or fall deeper into drought.

Because each ISM trace is shifted by one year relative to the previous trace, it is possible to study how starting with different inflow values impacts the system. The ensemble of streamflow traces generated with the ISM example provided in Figure 9.2 is shown below in Figure 9.3. The figure illustrates the repetitive sequencing and bounds of traces generated with ISM.

Model year	Natural flow record year	Trace 1	Trace 2	Trace 3	. . .	Trace 72	Trace 73	Trace 74	. . .	Trace 111	Trace 112
2020	1906	1906	1907	1908		1977	1978	1979		**2016**	**2017**
2021	1907	1907	1908	1909		1978	1979	1980		**2017**	1906
2022	1908	1908	1909	1910		1979	1980	1981		1906	1907
⋮	⋮	⋮	⋮	⋮	↗↗	⋮	⋮	⋮	↗↗	⋮	⋮
2058	1944	1944	1945	1946		2015	2016	2017		1942	1943
2059	1945	1945	1946	1947		2016	2017	**1906**		1943	1944
2060	1946	1946	1947	1948		2017	**1906**	**1907**		1944	1945

Figure 9.2

Index Sequential Method (ISM) example that uses the natural flow record (1906-2017) and modeling horizon of 41 years (2020-2060). The method is desribed in the text. (Source: adapted from Reclamation)

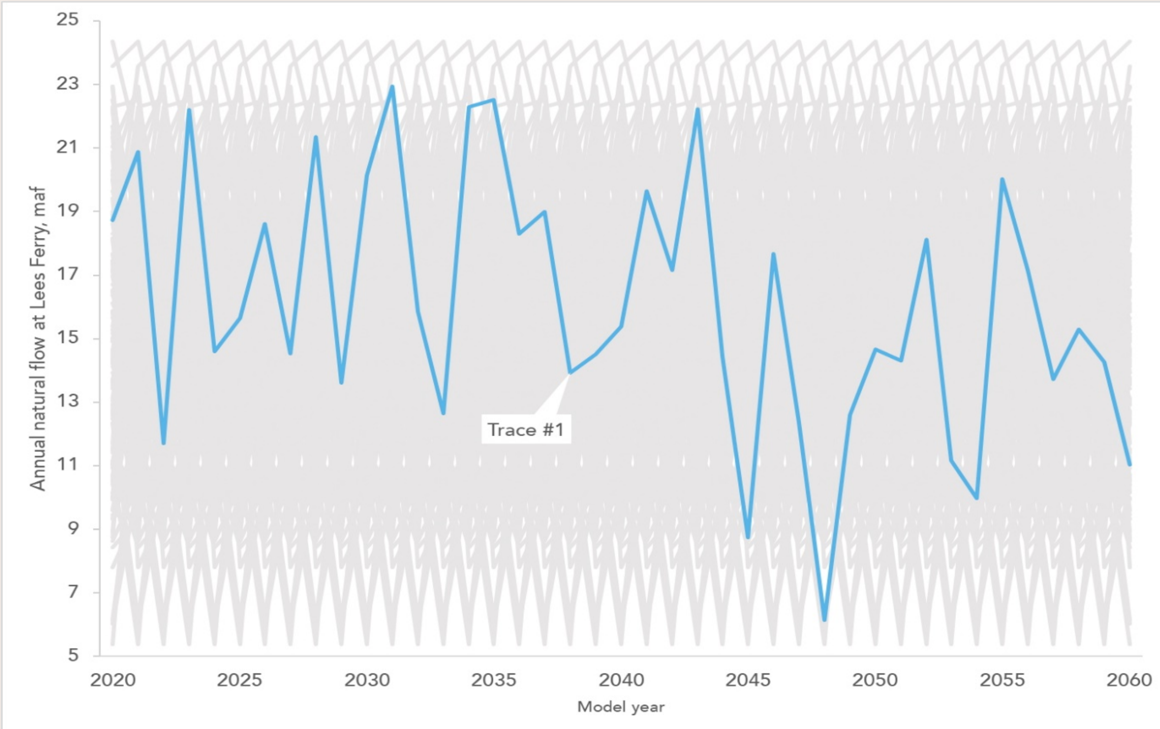

Figure 9.3

Example ensemble of 112, 41-year natural flow traces for the Colorado River at Lees Ferry generated with ISM as described above. The blue line shows Trace #1 in Figure 9.2: the natural flows from 1906-1946. (Data: Reclamation)

Advantages and limitations of ISM

Like the other methods described in this report that are used to develop hydrologic inputs to Reclamation's operations and planning models, ISM has advantages and limitations; a summary is given in Table 9.1 and discussed in the text below.

The primary advantage of ISM is that, by using the naturalized historical hydrology directly, it reflects the physical processes, climatological conditions, and watershed characteristics that were in place when the streamflow observations were made. There is little concern that traces sampled directly from the historical time series might misrepresent the processes, conditions, or characteristics that combined to produce the those streamflows. From that primary advantage follow some of the additional benefits listed in Table 9.1: ISM preserves the characteristics of the historical time series, i.e., it preserves the cross-correlations among basin locations, serial correlations from year to year, persistence from month to month, and the mean, variability, and other statistics of the historical record.

Table 9.1

Summary of advantages and limitations of using the index sequential method

Advantages	Limitations
Retains credibility because it is based on observed values	Full record includes the unusually wet years of the early 20th century—though sub-periods from the full record are often used
Preserves the historical frequency distribution and summary statistics	Cannot generate event magnitudes, durations, or frequencies outside of the observed record
Nonparametric, so not subject to errors in distribution fitting	Does not provide enough variety of "statistically plausible" potential sequences for planning analyses (Prairie et al. 2006)
Preserves historical persistence and spatial relationships, i.e., autocorrelations and cross-correlations	Cannot represent changes to relationships and dependencies that may arise from future climate change
Allows systems analysis under alternative initial inflows	Statistical interpretations of results are complicated due to lack of independence or randomness of traces
Traces are reproducible	Limited representation of uncertainty

The primary limitation of ISM is the converse of its advantage: it limits analyses to the streamflow ranges, durations, and frequencies seen in the historical record. ISM is not a stochastic method and therefore novel streamflows are not produced. As Kendall and Dracup (1991) explain,

> "Streamflow is a random process. The historic hydrologic record is one realization of this random process. Wrapped hydrologic sequences of the historic record are not other realizations of a random process in a strict sense even though they are treated that way when probability curves are developed."

Nor are the sequences independent (Labadie et al. 1987; Ouarda, Labadie, and Fontane 1997). Ouarda et al. warn that, "An additional concern with ISM has been the statistical dependency of the extracted sequences because of the overlapping structure of synthetic data records generated." One hundred twelve ISM traces generated from a single, 112-year sample are not the same as 112 independent streamflow traces. In statistical terms, the traces are very highly correlated with each other—a phenomenon one would not encounter outside of the ISM technique (Staschus and Kelman 1989). According to Salas (1992), "A major drawback with this procedure [ISM] is that the resulting set of N input series yields N outputs which are not independent and, as a consequence, the outputs have less precision."

The lack of randomness and independence, two basic premises for statistical analysis of hydrological time series (Naghettini 2016), can be illustrated with a graph of the low-flow sequences found in the example traces used in Figure 9.2 and Figure 9.3. In Figure 9.4, the minimum 5-year annual average streamflow at Lees Ferry for each trace is shown as a single bar. The lowest 5-year minimum, 9.55 maf, which corresponds to the calendar year 2000–2004 annual average, reoccurs in 37 of the 112 traces.

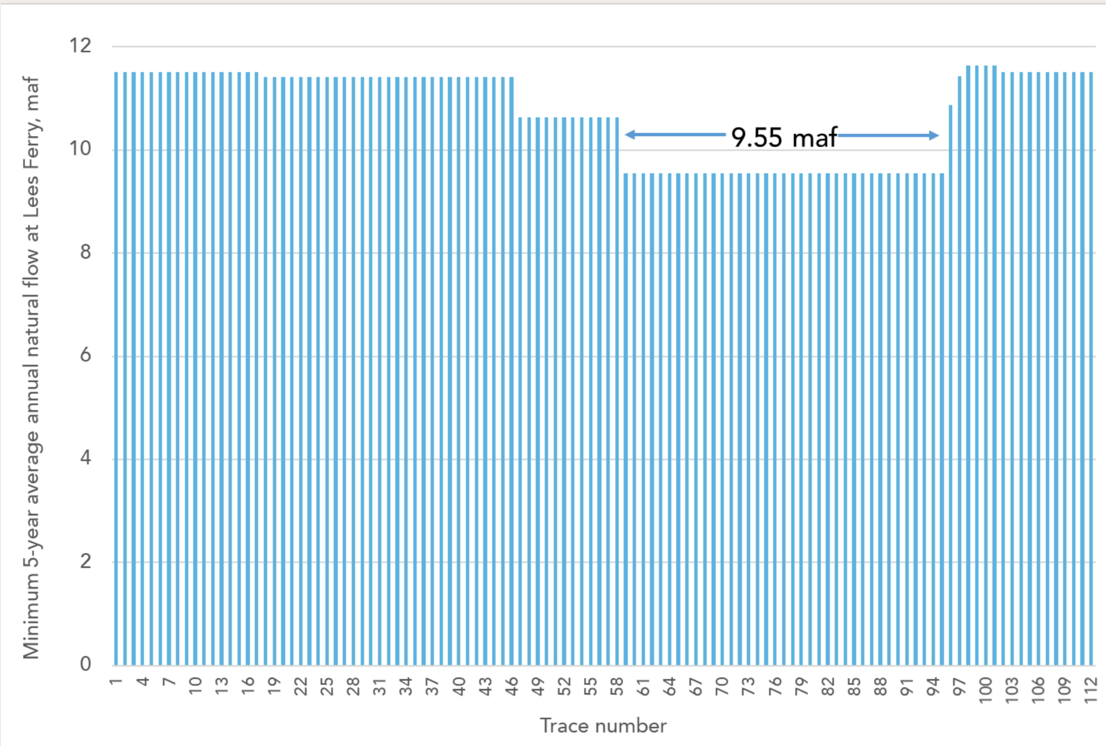

Figure 9.4

Minimum 5-year average annual flow at Lees Ferry in each of 112 ISM traces generated from the full natural flow hydrology (1906–2017) and the 2020–2060 planning horizon. (Data: Reclamation)

The chart shows that there are a handful of unique 5-year minima, not dozens of different 5-year minima as might be expected from an ensemble of independent traces of a continuous random variable like streamflow.

Consideration should be given to how ISM results are interpreted. ISM provides the odds of a particular outcome only if history repeats itself. ISM does offer multiple, different streamflow traces. The hazard is that tests of the system against an ensemble of ISM traces might be interpreted as tests of a random distribution of future events, reflecting the uncertainties inherent in natural variability. Srinivas and Srinivasan (2005) consider ISM to be a simple technique that may not model the data adequately, motivating the development of new multi-site methods.

Even so, the value of ISM's preservation of streamflow correlations in both time and space in the Colorado River Basin should not be underestimated. Reproducing the significant correlations throughout the basin using parametric methods is not a trivial exercise. See Lee and Salas (2006) for a breakdown of all the month-by-month and site-to-site cross-correlations among the 29 inflow points in Reclamation's Colorado River Simulation System (CRSS) model and a description of their efforts to extend the natural flow record while maintaining those correlations. Nowak et al. (2010) also discuss the drawbacks of taking a parametric approach to disaggregating synthetic sequences in time and space.

ISM applications

The conception of ISM and its application in the Colorado River Basin coincided with advances in computing power. The first documented ISM-type application is found in Reclamation's 1969 "Report of the Committee on Probabilities and Test Studies to the Task Force on Operating Criteria for the Colorado River," in which test streamflow sequences were described that were created by wrapping the beginning of the historical record to the end. Multiple test sequences, including ones selected to stress the system, were used in 146 computer runs to study various demand and operations scenarios (Reclamation 1969).

Since then, ISM-generated inflow sequences have been used as inputs to the Colorado River Simulation Model (CRSM) and its successor, CRSS, and have provided the primary basis for Colorado River Basin planning for several decades (see Chapter 3 for descriptions of these models). Most of the studies have involved sampling blocks from the full natural flow record that starts in 1906. The assumption implicit in the use of the full record is that the observed long-term mean and variance of natural flows in the Colorado River Basin are stationary and representative of the future. However, ISM traces that are sampled from the full record contain the wet period of the early part of the 20th century, which, in the context of the paleohydrologic record (see Chapter 10), is one of the wettest sequences in the past 1200 years. The mean annual flow from 1906 to 1925 is about 17.9 maf, well above the full record mean of 14.8 maf and over 30% above the most recent 30-year mean of 13.3 maf.

To address the issue of repeating the unusually wet years of the early 20th century in simulations, Reclamation has explored applying ISM to other segments of the hydrologic record (Table 9.2). Most recently, in response to an extended drought and the need to support drought contingency planning efforts, Reclamation and stakeholders in the basin identified 1988 to 2016 as a period that could provide more perspective on system risks (see Table 9.2). This sequence of years is referred to as the "Stress Test" hydrology. It is compared to the full record in Figure 9.5.

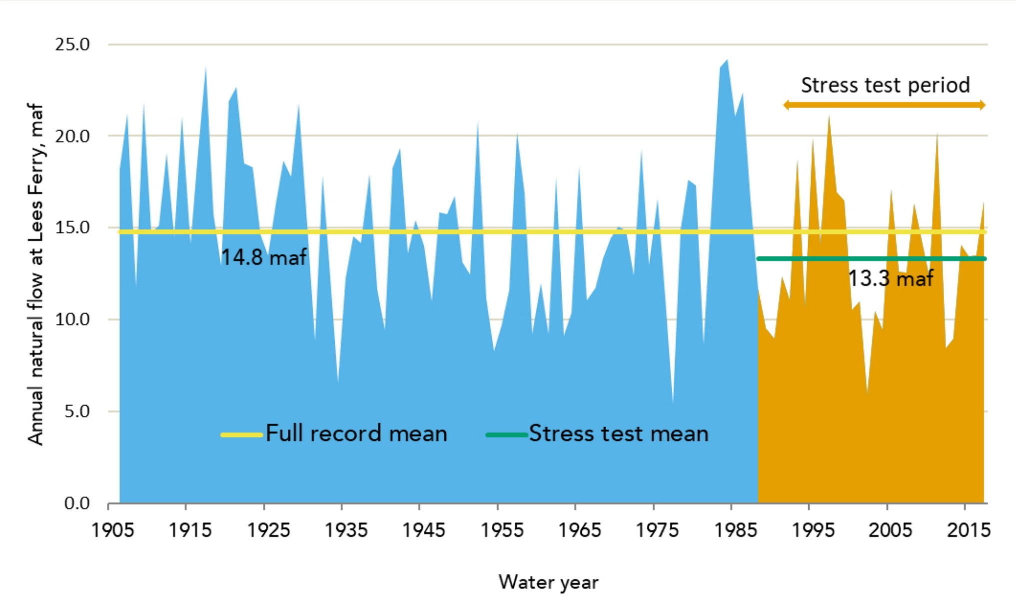

Figure 9.5

Full-record and stress-test period annual natural flows at Lees Ferry (1906-2017). (Data: Reclamation)

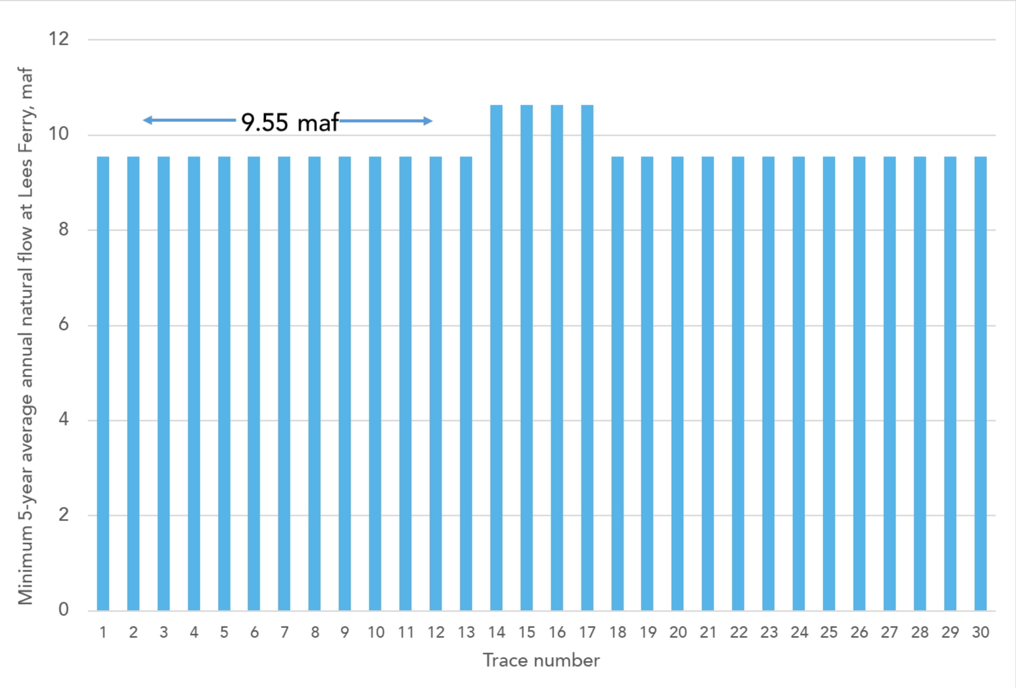

Figure 9.6

Minimum 5-year average annual flow at Lees Ferry in each of 30 ISM traces generated from the stress test natural flow hydrology (1988–2017). (Data: Reclamation)

The stress test trace length (2020–2049) contains the same number of years as those in the stress test hydrologic record (1988–2017, 30 years), so each of the 30 ISM traces contains the same streamflow values and has identical means, variances, maxima and minima. The minimum 5-year flow sequence in the stress test hydrology is shown in Figure 9.6. Again, the drought of 2000–2004 is repeated, in this case, in 26 out of the 30 traces. However, because the stress test period does not include the high flow years of earlier parts of the record, the stress test traces do not offer the same storage recovery opportunities as ISM traces generated from the full record.

An example of results from CRSS runs made in August 2018 with these two ISM inflow datasets (full hydrology and stress test hydrology) is shown in Figure 9.7. The system projections in the figure include assumptions about demands. The figure shows projected Lake Mead elevations for water years 2018 to 2026, when the Interim Guidelines will be reviewed (U.S. Secretary of the Interior 2007).

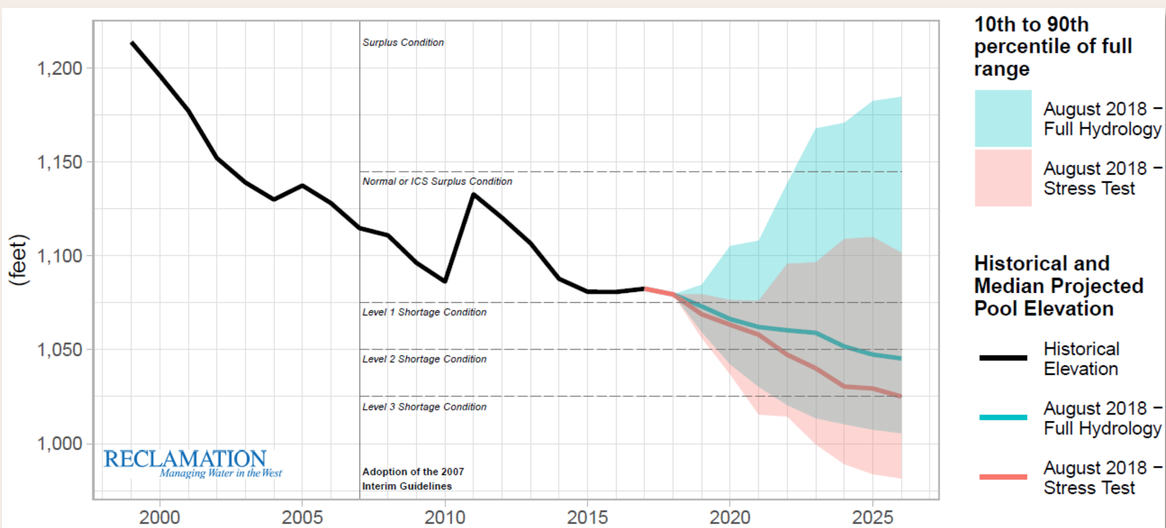

Figure 9.7

Lake Mead end-of-December elevation results from CRSS runs made in August 2018 that use the full record hydrology and the stress test hydrology (system projections include assumptions about demands). (Source: Reclamation)

Recent Reclamation studies and reports that have relied at least partially on ISM-generated inflows are summarized in Table 9.2.

Reclamation and others have recognized the need to test Colorado River Basin operations under novel hydrologic scenarios (Prairie et al. 2006). The concern has been that the observed historical record, with or without ISM, does not adequately represent the river's natural variability and therefore the vulnerability of the system to severe, low-frequency events. To address this concern, other methods that use the historical hydrology, specifically stochastic methods, have been pursued. Those methods are described in the next section. Methods that use paleohydrology or climate change-informed hydrology are described in Chapters 10 and 11, respectively.

Table 9.2

Summary of recent reports and analyses that have used ISM on the observed natural flow record. (Source: Reclamation)

Report or Analysis	Scenario Name	Years Included in ISM	Mean, maf	Planning Horizon	Number of Traces	Trace Lengths (years)[5]
Final EIS: Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead[1], 2007	Direct Natural Flow Record	1906–2005	15.0	2008-2026	100	53
Colorado River Basin Water Supply and Demand Study[2], 2012	Observed Resampled	1906–2007	14.9	2012-2060	102	49
Minute 323 Binational Negotiations	Pluvial Removed	1931-2012	14.0	2017-2026	82	44
Ten Tribes Partnership Tribal Water Study[3], 2018	Observed Natural Flow Record	1906-2015	14.8	2017-2060	110	44
Drought Contingency Planning[4], 2019	Full Hydrology	1906-2016	14.8	2020-2026	111	41
	Stress Test Hydrology	1988–2017	13.2	2020-2026	30	30

[1]The Final EIS also applied ISM to the 1244 year long paleo record.

[2]The Basin Study used multiple hydrology scenarios including ISM applied to the paleo record, a hybrid approach combining the paleo and observed records, and climate change based hydrology.

[3]The Tribal Water Study also used climate change based hydrology.

[4]The Drought Contingency Planning process took six years. The years that ISM was applied to and the planning horizon reflect those used at the end of the process (Spring 2019).

[5]In some cases, the length of the traces extend beyond the planning horizon so that continued effects of a policy can be understood, even if they extend beyond the years the policy is in effect.

9.3 Stochastic methods

The concept that natural streamflow is the result of random processes is fundamental to stochastic hydrology methods. The historical record is a single realization of those random processes, and though we can be fairly certain that the historical streamflow time series will not recur, it contains information that can be extracted and applied in the generation of novel streamflow traces. Stochastic hydrology methods use that extracted information to generate new streamflow traces, simulating the random nature of streamflow time series while maintaining fidelity to many characteristics of the historical record. By generating multiple unique, equally likely traces, these methods address the uncertainty inherent in the natural processes that result in streamflow (Bras and Rodríguez-Iturbe 1985). Generally speaking, parametric stochastic methods attempt to reproduce the statistical properties, particularly mean and variance, of the historical data. Nonparametric stochastic methods use the data at hand, and thereby also maintain fidelity to the historical data without requiring assumptions about the underlying probability distribution. Both categories offer the opportunity to look at longer and more intense sequences of low (or high) flows. See Loucks and van Beek (2017) and (Vogel 2017) for recent overviews of stochastic streamflow generation methods.

Reclamation has been exploring the use of stochastic hydrology for input to its long-term planning models since the 1970s, including supporting development of LAST (Lane's Applied Stochastic Techniques), a computer package for generating stochastic streamflow traces (Reclamation 1985; Lane and Frevert 1988; Frevert and Cheney 1988), and SAMS (Stochastic Analysis Modeling and Simulation; Salas et al. 2001; Sveinsson et al. 2007). Another stochastic streamflow generation package, SPIGOT, was developed at Cornell (Grygier and Stedinger 1990) and applied to the Colorado River by Kendall and Dracup (1991), and by Tarboton (1994) in the Severe Sustained Drought studies (Powell Consortium 1995). See Table 9.3 for more information about applications of these packages in the Colorado River Basin. All of these packages use parametric methods.

Parametric stochastic methods

As explained at the beginning of this chapter, parametric approaches require mathematical approximation of the form of the underlying distribution; i.e., a particular PDF that fits the observed streamflows and is therefore assumed to represent the larger population of streamflows of which the observed record is a sample. If the observations were normally distributed, stochastic traces could be generated by simply applying normally distributed random noise to the PDF equation. However, hydrologic data are rarely normally distributed (e.g., they are typically non-negative), so they must be normalized or transformed prior to application of a normal random term. The PDF that fits the observations indicates the transformation method. For example, observations that are lognormally distributed (i.e., the PDF is lognormal, Figure 9.1) are transformed by taking the log of the observations. The parameters of the transformed observations are determined and used, with a stochastic component (i.e., the random noise), to generate intermediate stochastic values that are then back-transformed to yield a final, stochastic streamflow trace. In the lognormal example, the final stochastic streamflow values are obtained by taking the antilog of intermediate stochastic values (US Army Corps of Engineers 1971). The back-transformation step may not faithfully preserve the historical statistics, however, because the procedure reproduces the statistics of the transformed observations rather than those of the actual (un-transformed) observations (Tarboton 1994).

These are the basic steps of parametric stochastic streamflow generation. Refinements to better approximate real-world streamflows include incorporating persistence, or serial correlations, especially for shorter time steps, and spatial correlations for multi-site applications. The stochastic streamflow trace may simulate multiple inflows to a larger system, or it may simulate a large streamflow downstream of one or more confluences. In these cases, aggregation or disaggregation of generated traces may be required. Further refinements to incorporate parameter uncertainty have also been made. Background on the evolution and application of parametric stochastic streamflow methods can be found in Marco, Harboe, and Salas (1993) and Vogel (2017).

One of the primary challenges facing water resources researchers and planners in applying the basin's historical time series is how to use it to generate streamflow traces that allow study of the non-stationary hydroclimate. Parametric stochastic approaches to addressing non-stationarity that rely exclusively on historical hydrology focus on modifying the parameters of the PDF derived from historical observations. This approach, in a highly simplified example, entails representing the non-stationarity with a new estimate of mean annual flow, which shifts the historical, observed PDF to the right or left along the x-axis (Figure 9.1). Stochastic flows are then generated using that relocated PDF. However, this assumes that both the choice of PDF (lognormal, gamma, etc.) remains the correct one, and that the other parameters that describe that PDF stay the same. In other words, it assumes that only the average is affected by the changed conditions, and that the scale and shape of the distribution, i.e., the variance and symmetry, are stationary. If the stochastic model includes temporal or spatial correlation terms, consideration must be given to the stationarity of those components as well. Serinaldi and Kilsby (2015) summarize these considerations and additional uncertainties associated with this approach to non-stationarity. Bender, Wahl, and Jensen (2014), who looked at Rhine River flows, demonstrated a method to diagnose the dependencies among distribution parameters. Khaliq et al. (2006) offers an extensive review of parametric approaches to non-stationarity.

Limitations

The advantages of parametric methods were identified at the beginning of this chapter. The limitations of parametric stochastic approaches include: 1) there is at least some loss of fidelity to the original data's characteristics through the transformation steps; 2) the observations may not clearly fit any of the common probability distributions or are multimodal; 3) disaggregation in time or space may require very large numbers of parameters; 4) potentially unrealistic, even negative, values may be generated; 5) nonlinear relationships are not represented, e.g., temporal and spatial correlations may vary in wet or dry episodes; 6) large samples cannot repair the bias in an incorrectly specified PDF; and 7) the implicit assumption of stationarity may be inappropriate (Salas et al. 1980; Tarboton 1994; Lall 1995; Sharma, Tarboton, and Lall 1997; Prairie et al. 2006; Milly et al. 2008; Scott 2015; Naghettini 2016; Vogel 2017).

Comparisons to ISM

Labadie et al. (1987), Frevert and Cheney (1988), Staschus and Kelman (1988), Kendall and Dracup (1991), and Ouarda, Labadie, and Fontane (1997) each compared the use of ISM with parametric stochastic methods. Most of the studies came to the conclusion that ISM is a reasonable technique for the purposes to which they were applied (primarily for analysis of hydropower and reservoir operations) and yielded similar results to stochastic techniques. Frevert and Cheney (1988) did not offer an overall assessment but cautioned that practitioners should understand that the variability in the ISM traces could be too low, citing streamflow records that are frequently broken. Ouarda, Labadie, and Fontane (1997) concluded that ISM is a valid procedure. Staschus and Kelman (1989) and Kendall and Dracup (1991), who used SPIGOT to generate stochastic traces and compared them to ISM traces, point out that, though their studies demonstrated that ISM was adequate or superior for the applications they examined, for studies looking at the extremes, or tails, of a distribution, other approaches may provide a more accurate representation. Finally, because parametrically derived streamflow traces are generated from probability distributions, probabilistic interpretations are straightforward and results lend themselves to estimates of confidence limits (Naghettini 2016) while this is not true of ISM-generated traces.

The studies that have used parametric stochastic methods on Colorado River Basin historical flows are summarized in Table 9.3. In the past twenty years, the number of such studies has fallen off; most of the research since the late 1990s that uses stochastic approaches to streamflow generation in the basin has focused on nonparametric methods.

Nonparametric stochastic methods

As mentioned above, nonparametric methods rely on empirical data, i.e., the observed hydrology, more directly, rather than fitting the observations to a theoretical PDF and then generating stochastic flows from that PDF. All of the nonparametric methods described here rely on resampling the historical record in some way. Research efforts have shifted to nonparametric approaches for a number of reasons, but primarily because the true form of the distribution of the population of streamflows is unknown, and it is therefore possible that the probability distribution that best fits the observations (i.e., a sample from the population) is not the correct one for the population. Lall (1995) explains the issue:

> Usually, the hydrologist has little physical or theoretical guidance as to the specific form of the target function. The traditional exercises amount to choosing between a small set of prescribed curves to fit the data at hand. What is one to do when the naked eye discerns structure in the data, and yet none of the usual candidates fit well? How does one choose between two models that fit equally well in terms of a global measure (e.g., likelihood, or sum of squared residuals), are parsimonious, and yet differ markedly in the details of the fit?...Questions like these invariably steer an investigator into the realm of nonparametric function estimation or "smoothing."

At least two nonparametric methods, kernel density estimation and nearest neighbor density estimation, have been used in studies that have generated stochastic Colorado River streamflows. The two methods are briefly described here.

Unlike parametric methods, kernel methods estimate the overall form of the observations by analyzing smaller intervals, or bandwidths, of the data. The bandwidths are analogous to the bins in a histogram, but instead of estimating a uniform frequency for all values within a bandwidth, the frequency, or density, at each observation point is weighted based on its distance from the center of the bandwidth. In parametric methods, the overall density estimate is made based on the parameters of the entire set of observations. In the kernel method, observations outside each bandwidth have no influence on the density estimate for observations within the bandwidth. The bandwidths are advanced, like a moving average, through all of the observations. The resulting set of local density estimates are aggregated to produce an overall, empirical density function for the entire observational dataset. The empirical density function looks like a smoothed histogram—the larger the bandwidth, the smoother the overall density function, and vice versa. Figure 9.8 illustrates an example application of kernel density estimation to July monthly flows on the Beaver

River in Utah. It offers a graphic comparison of the parametric fits of normal (Gaussian), lognormal and 3-parameter lognormal PDFs to the nonparametric, empirical, kernel density estimate. Only the empirical density estimate captures the bimodal nature of the observations. In the kernel method, the empirical density function becomes the basis for generating stochastic streamflow traces (Lall 1995; Sharma, Tarboton, and Lall 1997; Breheny 2012).

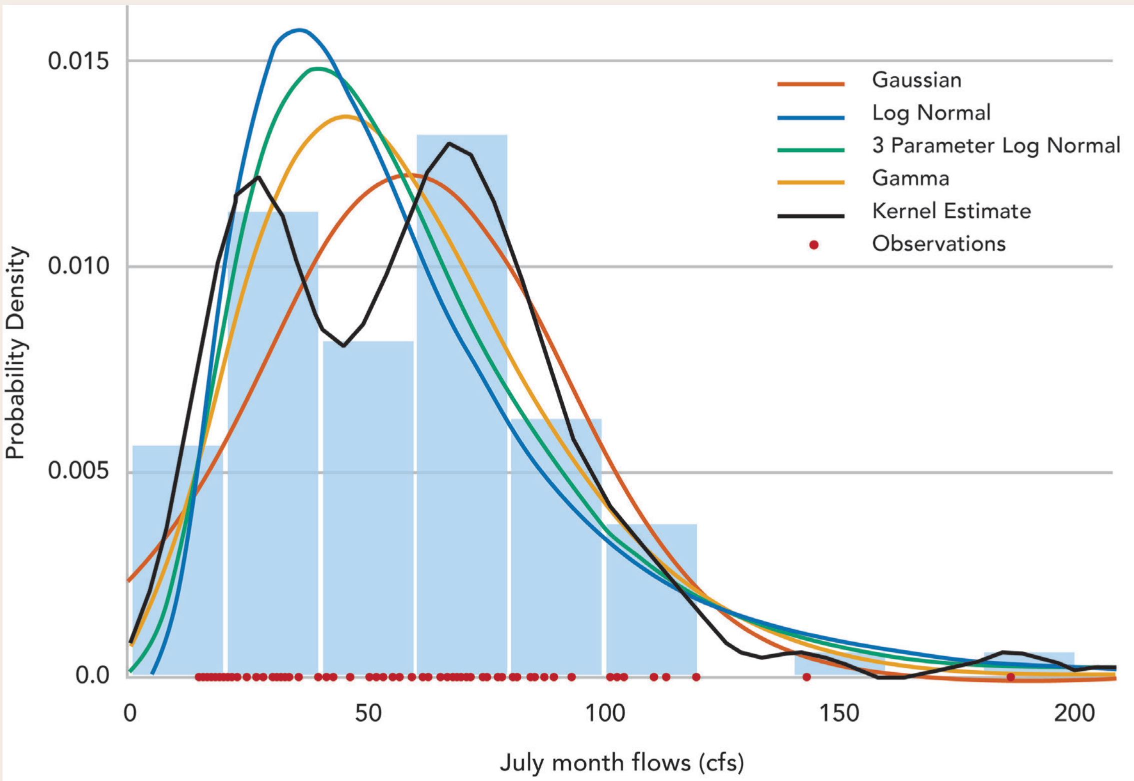

Figure 9.8

Example application of kernel density estimation to streamflows. (Source: Sharma, Tarboton, and Lall 1997)

Tarboton, Sharma, and Lall (1998) used kernel density estimation methods in their study of streamflow disaggregation. They observed that the technique is better than parametric techniques at capturing the wet-year vs. dry-year effects on seasonal variability. The primary shortcoming of the method is that it is computationally intensive, with the computational load driven by the size of the matrix resulting from the bandwidth length and the number of parameters used to define the local density estimates. Sharma, Tarboton, and Lall (1997) identify the potential for the method to produce negative flow values.

Prairie et al. (2007) and Nowak et al. (2010) also took nonparametric approaches to disaggregating streamflow. Prairie et al. (2007) disaggregated annual streamflows to monthly flows and Nowak et al. (2010) disaggregated annual streamflows into daily flows and further disaggregated those daily flows spatially to three locations. The methods these authors used for both stochastic streamflow generation and disaggregation were K-NN, or nearest neighbor, methods.

Nearest neighbor methods, pioneered by Lall and Sharma (1996) for application to hydrologic time series, also calculate local density estimates rather than relying on an assumed PDF for the entire set of observations. The term "nearest neighbors" refers to observations that are closest in Euclidean space, i.e., the closest points on a graph of observations vs. frequency or vs. other observations. The local density estimates are based on weighted averages of the K (number of) nearest neighbors to the individual observed flow values, with nearer neighbors being given a greater weight than more distant neighbors. The original K-NN approach resulted in generated values that were sampled from the historical data directly and thus did not introduce new streamflow values, though it did produce new sequences (Prairie et al. 2006). The K-NN method offered by Lall and Sharma (1996) was modified by Prairie et al. (2006) to resample the residuals from local regressions on sets of nearest neighbors and add those residuals to the local means, thereby producing potentially novel streamfow values.

Sharifazari and Araghinejad (2015) extended the modified K-NN model of Prairie et al. (2006) to capture the temporal and spatial streamflow dependence in the Sirwan River Basin in Iran. They also demonstrated a method to shift the generated flows lower or higher by biasing the residuals sampled in the method. According to the authors, this shift could be applicable to generating climate change-informed traces.

Applying paleohydrology, Prairie et al. (2008) took advantage of the most salient features of the reconstructed tree-ring record, i.e., the hydrologic state (wet or dry) and duration, to guide K-NN resampling from the historical, observed record. This effort generated streamflow traces that both preserved the range of flow magnitudes seen in the historical record and provided novel streamflow sequences. This study is described in more detail in Chapter 10.

More recently, and also taking advantage of the tree-ring record, Erkyihun et al. (2016) applied K-NN methods in a study using low-frequency climate signals to generate annual flows at Lees Ferry. The authors discerned climate signals in the reconstructed tree-ring streamflow record that are attributed to the Pacific Decadal Oscillation and Atlantic Multi-decadal Oscillation climate indices. They used K-NN methods to generate annual flows at Lees Ferry conditioned on those signals. An advantage of using the climate signal is that autocorrelations do not have to be explicitly specified in the annual streamflow generation model—they are implicit in the climate signals.

Parametric approaches to hydroclimatic non-stationarity were described above. Nonparametric approaches have focused primarily on climatic data time series rather than streamflow (Vogel 2017).

Limitations

Nonparametric methods, because they resample from the historical record, are heavily dependent on the length of that record and the variability and range of values therein. The K-NN method depends on a sample size large enough to contain sufficient nearest neighbors to produce a meaningful analysis (Lall and Sharma 1996; Prairie et al. 2006). Prairie et al. (2006) also commented that K-NN did not capture interannual variability well. Nonparametric methods applied to monthly time steps have difficulty with continuity in the transitions from the last month of one year to the first month of the following year (Prairie et al. 2007). Finally, kernel-based methods require disaggregation techniques that are “inefficient and cumbersome” (Prairie et al. 2007; see also Tarboton, Sharma, and Lall 1998, and Nowak et al. 2010).

Comparisons to ISM

Few formal comparisons have been made between ISM and nonparametric methods. Prairie et al. (2006) found that the modified K-NN method performed better than ISM at capturing features of the monthly flows, though the comparison was somewhat hampered by the relatively short traces produced by ISM. Also, nonparametric stochastic methods, like parametric methods, generate streamflows probabilistically, and therefore are more amenable to probabilistic interpretation.

Hybrid stochastic methods

There have been some efforts to combine parametric and nonparametric approaches to address the limitations of both types of methods in stochastic streamflow generation. These hybrid, or semi-parametric, methods usually apply the parametric and nonparametric methods during different steps of trace generation. Srinivas and Srinivasan (2005) and Herman et al. (2016) both used parametric methods to pre-standardize observations and then used nonparametric resampling methods to generate streamflow traces.

Other stochastic methods

More recent research on stochastic streamflow generation has applied "copulas" or multivariate PDFs that capture the dependencies between variables. Copula methods can be either parametric or nonparametric (Lee and Salas 2011; Hao and Singh 2012; Gold 2017). Hao and Singh (2012) used a copula method to develop a joint probability distribution for monthly Colorado River flows at Lees Ferry. They generated stochastic streamflow traces that simulate the temporal dependence between adjoining months with joint distribution functions for each pair of months.

Another recently developed approach is the multi-site multi-season maximum entropy bootstrap (M3EB) method (Srivastav and Simonovic 2014). The authors present a case study using four sites in the Upper Colorado River Basin: Colorado River near Cisco, Utah; Green River at Green River, Utah; San Juan River near Bluff, Utah; and Colorado River at Lees Ferry, Arizona. The method preserves the statistical characteristics and the temporal and spatial dependence structure of the historical data. The authors state that this method is capable of modeling both non-stationarity and seasonality.

A selected list of published applications of stochastic methods to generate streamflow traces from the historical hydrology in the Colorado River Basin is provided in Table 9.3. The list includes both parametric and nonparametric approaches. It does not include the many studies of stochastic approaches that have been applied to meteorological variables in the basin, or studies that do not use the historical hydrology directly, such as paleohydrology studies and climate change-informed hydrology studies. Those studies are described in Chapters 10 and 11, respectively.

Table 9.3

Selected studies in which stochastic methods were used to generate hydrologic traces from Colorado River Basin historical hydrology.

Type	Method or model name	Application	Reference
Parametric	LAST	Generated monthly streamflow traces for the Colorado River at Lees Ferry, with each month having a unique PDF transformation	Frevert and Cheney 1988
Parametric	SPIGOT	Generated annual, autoregressive, lag-one (AR-1) lognormal streamflow traces for the Colorado River at Lees Ferry	Kendall and Dracup 1991*
Parametric	SPIGOT	Used SPIGOT to disaggregate annual flows from tree ring reconstructions of the Colorado River at Lees Ferry in order to generate monthly streamflow traces for 29 locations in the Colorado River Basin	Tarboton 1994, 1995
Parametric	LAST	Generated monthly streamflow traces for 23 locations in the Colorado River Basin	Ouarda, Labadie, and Fontane 1997*
Nonparametric	Kernel-based technique	Compared SPIGOT vs kernel-based disaggregation methods for stochastic flows on the San Juan River	Tarboton, Sharma, and Lall 1998
Nonparametric	Modified K-NN	Compared monthly generated flows using modified K-NN to ISM flows and to parametrically generated (SAMS) flows at Lees Ferry	Prairie et al. 2006*
Parametric	LAST, SAMS and SPIGOT	Generated monthly streamflow traces for 29 locations in the Colorado River Basin from both spatial and temporal disaggregation of annual flows	Lee et al. 2007
Nonparametric	Modified K-NN	Disaggregated annual stochastic flows into monthly flows at four sites in the Upper Colorado Basin: Colorado River near Cisco, Utah; Green River at Green River, Utah; San Juan River near Bluff, Utah; and Colorado River at Lees Ferry, Arizona	Prairie et al. 2007
Nonparametric	K-NN	Generated annual streamflow traces at Lees Ferry by using the streamflow states from the tree-ring record to guide K-NN resampling from the historical record	Prairie et al. 2008

Type	Method or model name	Application	Reference
Nonparametric	K-NN	Generated daily streamflow traces for 3 locations on the San Juan River by using K-NN methods to disaggregate annual flows in both space and time	Nowak et al. 2010
Parametric	Copula	Generated monthly flows at Lees Ferry from joint probability distributions for each pair of months	Hao and Singh 2012
Nonparametric	M3EB	Generated monthly flows at Colorado River near Cisco, Utah; Green River at Green River, Utah; San Juan River near Bluff, Utah; and Colorado River at Lees Ferry, Arizona	Srivastav and Simonovic 2014
Nonparametric	WKNN	Derived low frequency climate signals from tree-ring flows and used K-NN to resample the historic observations to generate annual flows at Lees Ferry	Erkyihun et al. 2016

*Performed comparisons to ISM

9.4 Challenges and opportunities

This chapter has focused on the state of the science of applications of the observed, historical time series for long-term planning studies in the Colorado River Basin. All of the studies cited in this chapter use the historical time series, or characteristics of it, as inputs to, or benchmarks for, the various methods to generate synthetic streamflow traces. However, as described throughout the chapter, there are challenges to synthesizing streamflow traces from the historical record. Some of the higher level challenges, and opportunities to address them, are discussed below.

Challenge

Identifying the most appropriate method of incorporating historical hydrology in long-term planning in the Colorado River Basin is a key challenge. The full, observed historical record, especially when used with ISM, likely does not represent future hydrologic risk, but it is challenging to completely replace it because there is no clear best alternative. While Reclamation's use of a segment of the observed hydrology (the Stress Test) attempts to create a more realistic picture of risk, there is little guidance on which segments are most appropriate, and a shorter record reduces the range of hydrologic conditions available. Beyond ISM, there is much research but little consensus on alternative approaches to generating synthetic streamflow traces.

Opportunity

- One approach, informally suggested by Tarboton (pers. comm.), is that new streamflow generation models be tested against a comprehensive set of statistics. Extending that suggestion somewhat, a matrix could be established by Reclamation and basin stakeholders that identifies the most important features of synthetic traces and uses that matrix to guide research into new methods or to assess existing methods. Features in the matrix might include fidelity to particular historical statistics, ability to generate particular time steps, ability to simulate non-stationarity, ability to represent uncertainty, ease of implementation, ease of understanding, and robustness of inferences.

Challenge

One of the primary challenges facing water resources researchers and planners in applying the basin's historical time series is how to use it to generate streamflow traces that allow study of the non-stationary hydroclimate.

Opportunities

- Explore performing diagnostics on the parameters used in parametric stochastic streamflow studies in the Colorado River Basin to assess the dependencies between and among parameters and to assess the complexities involved in incorporating non-stationarity into them.
- Techniques for generating long-term streamflow sequences that blend historical observed hydrology with paleohydrology or climate change-informed hydrology (or both) offer substantial promise. The paleo record offers extremes, durations, and frequencies not seen in the observed record, and the climate change-informed hydrologies offer potentially altered climate patterns and regional shifts that are absent or undetectable from the observed and paleo records. For more information about these opportunities, see Chapters 10 (Paleohydrology) and 11 (Climate change-informed Hydrology).
- This chapter has focused on research into streamflow synthesis but there is a wealth of information about methods applied to synthesize time series for other hydrometeorological variables. A potentially useful effort might be to review approaches to other variables, and even other disciplines, for techniques that could be translated into streamflow synthesis techniques.

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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**