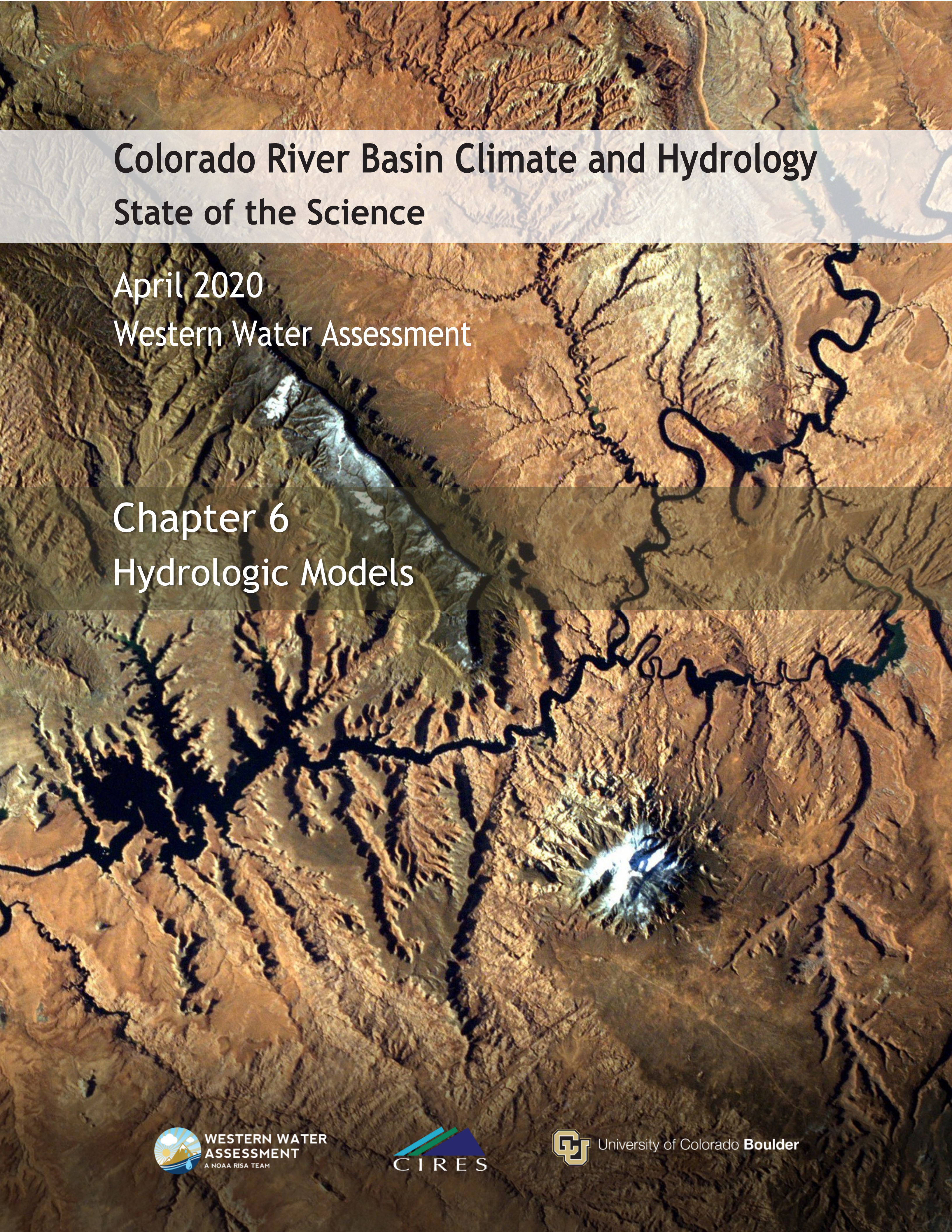

Colorado River Basin Climate and Hydrology

State of the Science

April 2020

Western Water Assessment

Chapter 6

Hydrologic Models

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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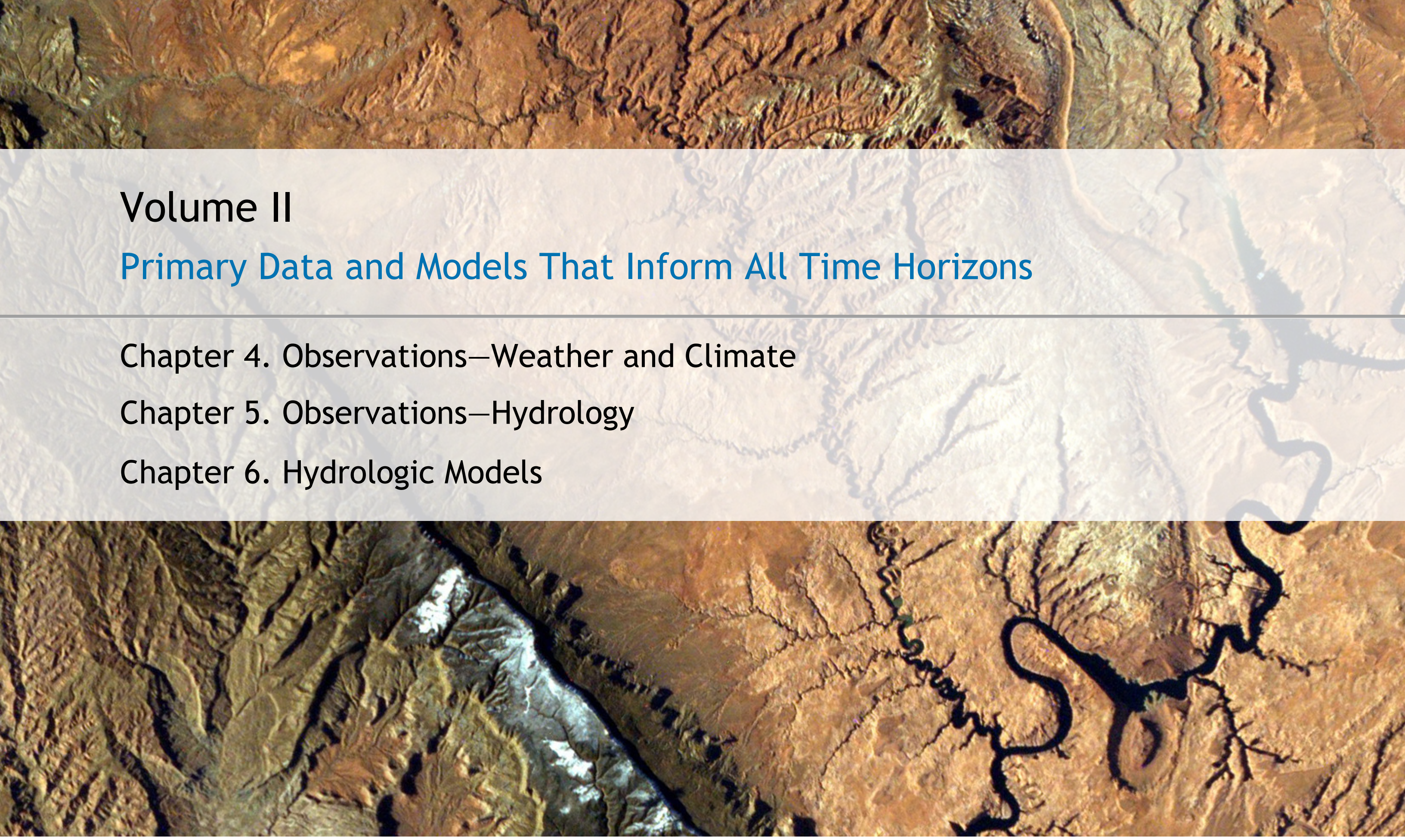

Volume II

Primary Data and Models That Inform All Time Horizons

Chapter 4. Observations—Weather and Climate

Chapter 5. Observations—Hydrology

Chapter 6. Hydrologic Models

Volume II of the Colorado River Basin State of the Science report focuses on primary data and models that are relevant across all time scales. While Volumes III and IV concentrate on short- to mid-term forecasting and long-term outcomes, respectively, the data and models addressed in this volume can be applied to Colorado River Basin studies performed at all of those time scales. The chapters in this volume describe how primary weather, climate, and hydrology data are collected and how datasets of other variables are built from primary data. A simple regurgitation of the vast literature about the primary data would not serve the goals of this report. The focus, instead, is on compiling, summarizing, and offering objective assessment of the data and the work that has been done to make it available. The objective of this volume is to be a uniquely useful reference for readers.

Chapter 4 is a reference for weather and climate data. It begins with a description of the methods and equipment that have been used to collect weather data, from the installation of the first weather stations in the basin in the late 1800s, to the emergence of remotely-sensed distributed data. It explains how point data become gridded datasets, how missing data are treated, how large scale data are disaggregated, which datasets have common source data, and how quantitative biases can be introduced. Knowledge about the methods behind, and idiosyncrasies of, the datasets, along with their strengths and weaknesses is presented to help readers determine which data sources are better fits for their applications. The chapter provides a detailed comparison of 11 gridded datasets. It explains things to consider when comparing values and trends from these datasets, and practical and scientific considerations when selecting a gridded dataset.

Chapter 5 is a reference to hydrology data—snowpack, streamflow, soil moisture, evaporation, and evapotranspiration—that are key inputs to streamflow forecasting and system modeling. Snowpack, soil moisture, and evaporation/evapotranspiration data are all gathered using three methods—in situ measurements, modeled estimates, and remote sensing. Chapter 5 provides a comprehensive description of the multiple data sets developed by each method, and an explanation of the advantages and limitations of each. Streamflow, on the other hand, has been measured in essentially the same way across the basin since measurements commenced at the end of the 19th century: stream gages that measure stream stage, which is subsequently translated to flow by a rating curve that is essentially an empirical hydraulic model of the gage site. This chapter explains the uncertainties in the gage record, which arise from measurement error but to a larger degree from errors in the rating curves. Measured streamflows are naturalized or deregulated for use in models. This process introduces more uncertainty, and the sources and implications of this uncertainty are thoroughly described in this chapter. The chapter closes with a summary of challenges and opportunities regarding hydrology data.

Chapter 6 is devoted to describing the evolution, application, and trade-offs of a number of runoff and land surface models that are the foundation of applications at the smallest time scale, streamflow forecasting, to the largest time scale, climate change projections. This chapter is complemented by Chapters 8 and 11, which place hydrology models in the context of forecasting and projection applications, and by Chapters 4 and 5, which describe the provenance and qualities of the data used to force and validate hydrology models. The advantages and disadvantages of the hydrology models are summarized and their usefulness for either forecasting or simulating climate sensitivity or both is assessed. Not surprisingly, the evolution of hydrologic models follows a path of increasing complexity, from empirical conceptual runoff models, to simple water balance models, which led to distributed land surface models and fine-scale physically explicit models and finally to coupled land-atmosphere models. Models of all of these types continue to be applied in the basin, and Chapter 6 describes the models currently in use in the basin and explores emerging models and approaches that could improve forecasting and projection. The chapter closes with an examination of knowledge gaps, challenges and opportunities for improvement.

Chapter 6

Hydrologic Models

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Key points

- With a range of hydrologic models readily available, it is important for prospective applications of models to articulate the objectives of the modeling as well as the requirements that the model must satisfy.
- A single model is likely designed for a specific application or context and may not be optimal for a wider range of uses.
- In the Colorado River Basin, the NWS models (streamflow forecasting) and the VIC model (sensitivity studies; climate change projection) have been the most-consulted hydrologic models for those respective applications. Each has varying capabilities and limitations.
- Increasing model complexity does not guarantee improved model performance. Complexity should be increased subject to the consideration of process needs, data sufficiency, computational feasibility, and ultimately the model's demonstrated performance.
- For some applications, such as streamflow forecasting at a river location, simpler models may continue to offer valuable and even superior performance for years to come.
- For other applications, such as understanding hydrologic sensitivity to climate change or hydrologic response to watershed changes, more complex process-oriented models are usually more appropriate.
- Calibration (parameter estimation) is almost always needed to achieve high-quality simulations in all hydrologic models, and it is easier to implement in simpler models than in computationally intensive complex models.

6.1 Overview

Hydrologic models are the foundation of broad range of applications in the Colorado River Basin, ranging from streamflow forecasting to trend analysis to climate change projection. This chapter provides an overview of hydrologic modeling, including perspectives on both model development and applications. There is some overlap with Chapter 8 (Streamflow Forecasting), but the additional applications of hydrologic models in basin water management and planning merits more thorough treatment of the models beyond their use in streamflow forecasting.

Hydrologic modeling refers to the use of simulations to characterize the likely behavior of real watershed features and systems (Allaby 2008). Hydrologic modeling can be applied to improve our understanding of hydrologic phenomena and how changes in, for example, pervious surfaces, vegetation, land use and weather and climate affect the hydrologic cycle. It is furthermore used to estimate runoff and water availability in the context of forecasts at timescales of hours to months, and projections over decades. The general components of a hydrologic model include meteorological inputs (such as precipitation and temperature), governing equations enforcing physical laws (e.g., mass continuity), parameters, parameterizations (the algorithms specifying processes such as infiltration), and the model structure, including the arrangement and connectivity of watershed components (canopy, snowpack, subsurface) (e.g., Singh 1995; Clark et al. 2015).

The hydrologic models currently applied in the Colorado River Basin and elsewhere arise from several distinct traditions. The use of hydrologic models in streamflow forecasting (Chapter 8) has deep and practical roots in civil engineering, where models were developed to support water systems design and management (Anderson and Burt 1985). The communities driving these forecasting models tend to be operational agencies. In contrast, hydrologic models used in the projection of future hydrology to support water supply assessment (e.g., Chapter 11), or in trend and variability analysis, are mostly driven by academic institutions and agency research laboratories. These latter models have a stronger heritage in earth system modeling and watershed process modeling.

Despite their different origins, all models have watershed (or land) representations that involve terms for the common input and output fluxes and states, such as precipitation, temperature, soil moisture, snow water equivalent (SWE), runoff and evapotranspiration (ET). How these components are represented within the models, the way runoff is calculated, and the spatial interpretation of the model's catchment area can vary significantly from one model to another.

Model complexity and spatial framework

Hydrologic models can be viewed along a general continuum of complexity. Complexity can refer to the number of processes represented in the model, the spatial resolution of the model, or the structure and configuration of the model. With the rise of supercomputing as a resource for hydrology, the range of complexity for regional (e.g., Colorado River Basin) model applications has become ever broader. The lower bound of complexity has been set by the lumped conceptual configuration of traditional operational models, while the advancing upper bound tracks the evolution of very high resolution watershed process modeling approaches that were previously applied only in small scale studies.

This widening range of model complexity has prompted much debate in the research and operational communities (e.g., Grayson, Moore, and McMahon 1992a; 1992b; Reggiani, Sivapalan, and Hassanizadeh 1998; Beven 2002; Sivapalan et al. 2003; Maxwell and Miller 2005; Beven and Cloke 2012; Wood et al. 2012), with differing perspectives on issues such as the adequacy of representations of physical processes, and the impact of real-world data limitations and uncertainty. What is clear, though, is that there is no one level of model complexity that is optimal for all applications. The following sections describe several general modeling approaches that differ in complexity, including the models used for the CBRFC's operational streamflow forecasting in the Colorado River Basin. (Streamflow forecasting itself is treated more thoroughly in Chapter 8.)

Conceptual and physical models

An initial distinction can be made between *conceptual* models and *physical* models—though models in each class may have elements of both, and these labels are inexact. Conceptual models have relatively simple representations of watershed attributes and processes, generally with no more than a dozen components. The relationships and linkages (fluxes of moisture or energy) between the components are typically controlled by adjustable parameters whose values may be only indirectly known from observations or otherwise deduced through calibration. The structure of the conceptual model is motivated by our understanding of the physics of the real world system (e.g., shallow and deep storage zones, percolation, radiation-driven snowmelt), but remains an extreme simplification of those physics. Conceptual models as well as physical models adhere to fundamental physical laws (such as mass and energy conservation) but conceptual models rely more much directly on external parameters to describe or specify hydrologic processes.

Physical models, also called process-based or mechanistic models, are generally more complex. They also contain many conceptual elements, but nonetheless represent the watershed attributes and processes with a higher degree of detail, and in arrangements that attempt to more closely mimic the storages of water and energy in the watershed and the fluxes between them. In contrast to conceptual models, physical models attempt to provide a more explicit representation of the hydrologic processes and the resulting hydrologic dynamics. Rather than allow an external parameter to directly control a process, they specify a physically informed equation describing the process (called a parameterization), which in turn is controlled by external parameters.

For example, in a conceptual model, the percolation rate from one storage zone to another may be determined by the storage amounts (states) and an external rate parameter specified in calibration. In contrast, the percolation in a physical model is determined by the storage states and an equation (and algorithm, a parameterization) that may calculate percolation also as a function of the soil properties assigned to the zones. These properties are often given by external parameters that may also be calibrated. As in conceptual models, the hydrologic responses in physical models are summations (i.e., an emergent behavior) of the hydrologic processes. Spatial and temporal variations in catchment characteristics are incorporated into physical models to a greater degree than conceptual models, and consequently the structure and configuration of the physical models more closely reflect the real world watershed.

Notwithstanding the above discussion, it is important to note that a physical model is almost always applied at a scale larger than that at which some processes occur (see Clark et al. 2017 for a discussion). For example, a hydrologic model implemented at 12-km grid resolution is much coarser than the real world scale at which processes such as percolation of meltwater through a snowpack, or infiltration through soil, take place (which may be on a scale of centimeters). Thus, even though the description of a process may be through a physical parameterization, the model does not explicitly resolve that process, and remains, in a sense, also conceptual, and usually requires some degree of calibration.

Spatial framework

A second important distinction between models refers to the spatial framework of the model. Spatial variability in topography, geology, soils, and vegetation affects the hydrologic responses within a watershed (Clark et al. 2017). The spatial framework in hydrologic models can be categorized as lumped, semi-distributed, or fully distributed (Figure 6.1).

Lumped models average the spatial variability across a watershed unit; semi-distributed models reflect some spatial variability; and fully distributed models process spatial variability by many small spatial units

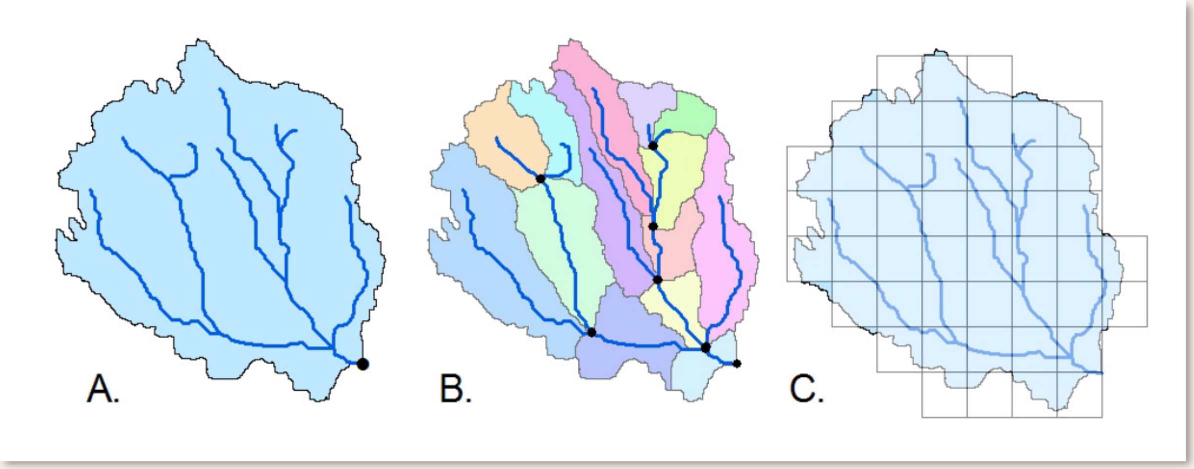


Figure 6.1

Schematic of the spatial frameworks in hydrologic models. **A**: Lumped model, **B**: Semi-distributed model by sub-catchment, **C**: Distributed model by grid cell. Runoff is calculated for each sub-catchment at the confluence points represented by the black dots in B. Distributed models calculate runoff for each grid cell, while lumped models calculate one runoff value for the entire catchment at the river outlet point represented by the black dot in A. (Source: Sitterson et al. 2017) (usually grid cells). The spatial framework of each of the classes of models is given in Table 6.1. The spatial framework is strongly associated with the model class: conceptual models generally have a lumped framework, while physical models generally have a more distributed framework. It should be noted that terms such as “distributed” and “lumped” are labels reflecting model intent, rather than definitive descriptions of the characteristics of a model, especially resolution. For example, a 12-km distributed model may have similar spatial resolution and degree of spatial averaging as a lumped model broken into three elevation zones for the same watershed. Also, physical models may incorporate sub-grid variability for selected watershed attributes, such as vegetation and elevation.

Four general classes of hydrologic models

The characteristics of four general classes of hydrologic models are summarized in Table 6.1 and described in greater detail in the text that follows. Note that the distinctions among the model types are not hard and fast, and some models may blend aspects of two or more classes. Table 6.1 serves as an organizing reference for this chapter and is referred to throughout.

Table 6.1

Summary of characteristics of four general classes of hydrologic models. Terms are defined in the text.

	Bucket-style conceptual models	Stand-alone land surface models and multi-model frameworks	Land surface models in a coupled ESM system	Explicit watershed process models
Examples in the Colorado River Basin	Sac-SMA, SNOW-17, Monthly Water Balance Model	VIC, SUMMA	Community Land Model, Noah-MP, HTESSEL	WRF-Hydro terrain-routing, DHSVM, GSSHA
Model structure	Conceptual	A mixture of physically explicit and conceptual components	A mixture of physically explicit and conceptual components	Physical, with fewer unresolved (conceptual) process components
Spatial framework	Lumped or semi-distributed	Distributed, but can have lumped components	Distributed	Distributed
Typical Resolution	3–30 km, or 10–1000 km^2 hydrologic unit	500 m–25 km	10–100 km	10–500 m

	Bucket-style conceptual models	Stand-alone land surface models and multi-model frameworks	Land surface models in a coupled ESM system	Explicit watershed process models
Primary applications in the Colorado River Basin	Operational streamflow forecasting, sensitivity analyses, coarse-scale climate-change impact analysis	Climate sensitivity analyses, climate change and variability impacts, streamflow forecasting	Weather and climate prediction, variability analysis, and climate projection	Hydrologic process studies (e.g., surface-groundwater interactions, ET modeling, snow hydrology), climate variability and change studies
Advantages	Computationally cheap, highly amenable to calibration (parameter estimation), agile for running ensembles and data assimilation, typically the highest- performing model for streamflow simulation and forecasting (within the calibration envelope)	Computationally feasible for most applications but requires high-performance computing for large domains, more process-oriented, maintains water and energy balance, more trusted for analysis beyond the calibration envelope, designed for regional to global implementation	Includes land-atmosphere feedbacks and a greater variety of process representations (including carbon cycle and dynamic vegetation in some cases), albeit at a coarser scale due to coupling in continental and global scale applications	Can represent hydrologic processes with more explicit detail and granularity, suitable for evaluation of high-resolution observations, can better represent explicit terrain and vegetation influence on hydrologic phenomena
Disadvantages	Conceptual representation and simplification of physical processes and extensive calibration limit the ability to simulate multiple outputs and project significantly beyond the calibration envelope	Computationally demanding relative to conceptual schemes, and structure, parameterization inflexibility can undermine performance and hamper calibration	Application in the coupled context in which atmospheric variables are often most important means that hydrologic quantities such as runoff or snowpack are less scrutinized and less calibrated	Computational demands restrict or degrade many applications, including long-range or large-domain simulation, comprehensive parameter estimation, and use of ensemble techniques

Bucket-style conceptual models

Conceptual models can be viewed as being based on the assumption that we know (or once *knew*) relatively little about the real world structure and functioning of a watershed, therefore we use a minimal structure, and infer parameters to directly control processes from observations. This strategy has been shown to work well where there are sufficient data for calibration and inputs, despite concerns about the extent to which the resulting parameters are overly tuned to the data.

At the time these models were initially developed in the 1960s and 1970s, the main motivation for the relatively simple representation of a watershed was to make the model supportable by the limited available weather and hydrology data at that time, which were almost entirely point-based (Chapters 4 & 5). But even today, these simple hydrologic models produce highly accurate simulations and forecasts that are difficult to outperform using physical models.

Bucket style conceptual models remain relatively simple, with lumped modeling units of small watershed areas, on the order of 10–1000 km^2. This lower complexity, with consequently lower computational demands, is

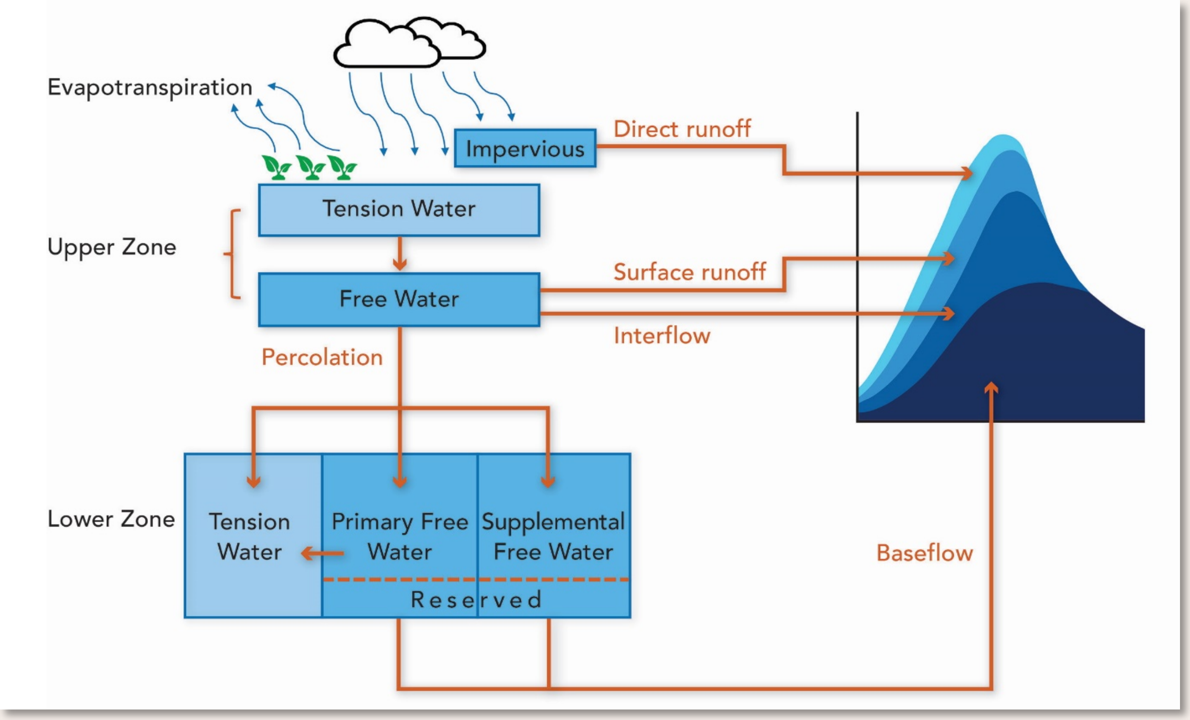


Figure 6.2

Conceptual flow diagram of the Sac-SMA model and a schematic representation of model output. (Source: adapted from NOAA NWS 2002) advantageous because it enables manual calibration in the model development phase, and facilitates forecasters' examining and iteratively updating their inputs, states, and outputs in real-time during the forecasting workflow. An example of a traditional lumped approach is provided in Figure 6.2.

The conceptual hydrology model whose output is most familiar to Colorado River stakeholders is the Sacramento Soil Moisture Accounting Model (Sac-SMA) used by the CBRFC and other National Weather Service (NWS) River Forecast Centers (RFCs) for operational streamflow forecasting (Figure 6.2). Sac-SMA has five soil storage types ("buckets"), each with an underlying physical rationale. For example, the upper zone tension water content bucket represents the portion of the soil column that experiences unsaturated flow and in which capillary pressure in soil pores resists drainage and lateral flow. Figure 6.3 shows an example of the output of Sac-

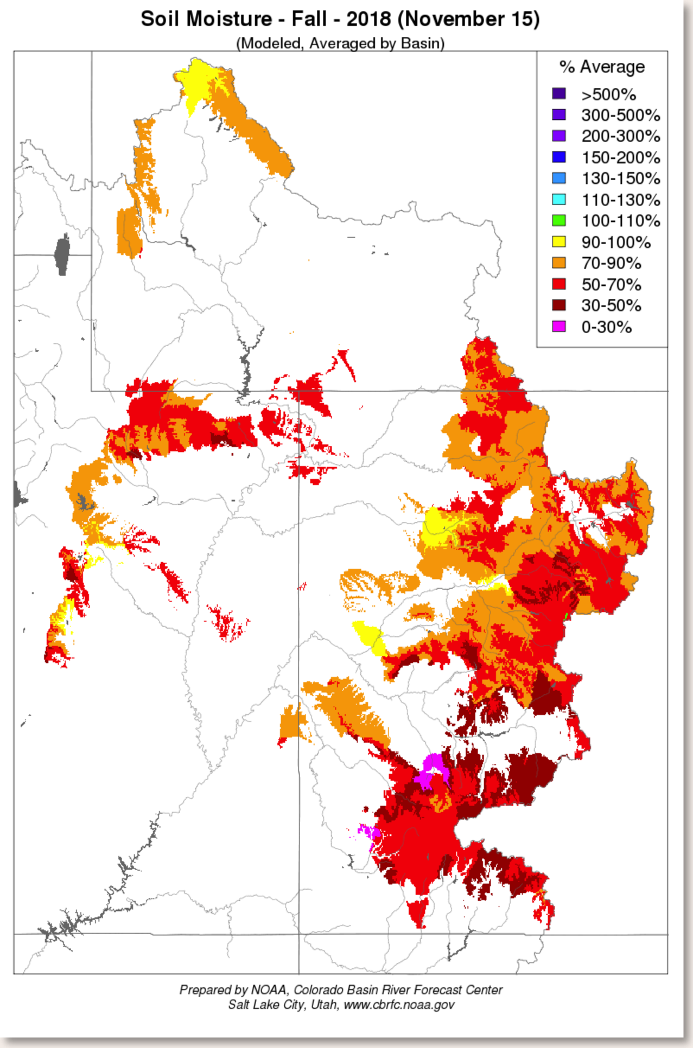


Figure 6.3
Example of model output of Sac-SMA for the upper Colorado River Basin. Note the lumped nature of the model output. (Source: NOAA NWS CBRFC; https://www.cbrfc.noaa.gov/wsup/sac_sm/sac_sm.php)

SMA, which is operationally paired with SNOW-17 (Anderson 1973), a temperature-index based conceptual snow accumulation and ablation model. See section 6.3 for a more detailed description of the NWS models.

Stand-alone land surface models (LSMs)

Stand-alone land surface models (LSMs) such as the Variable Infiltration Capacity (VIC) model are physical models and differ from conceptual

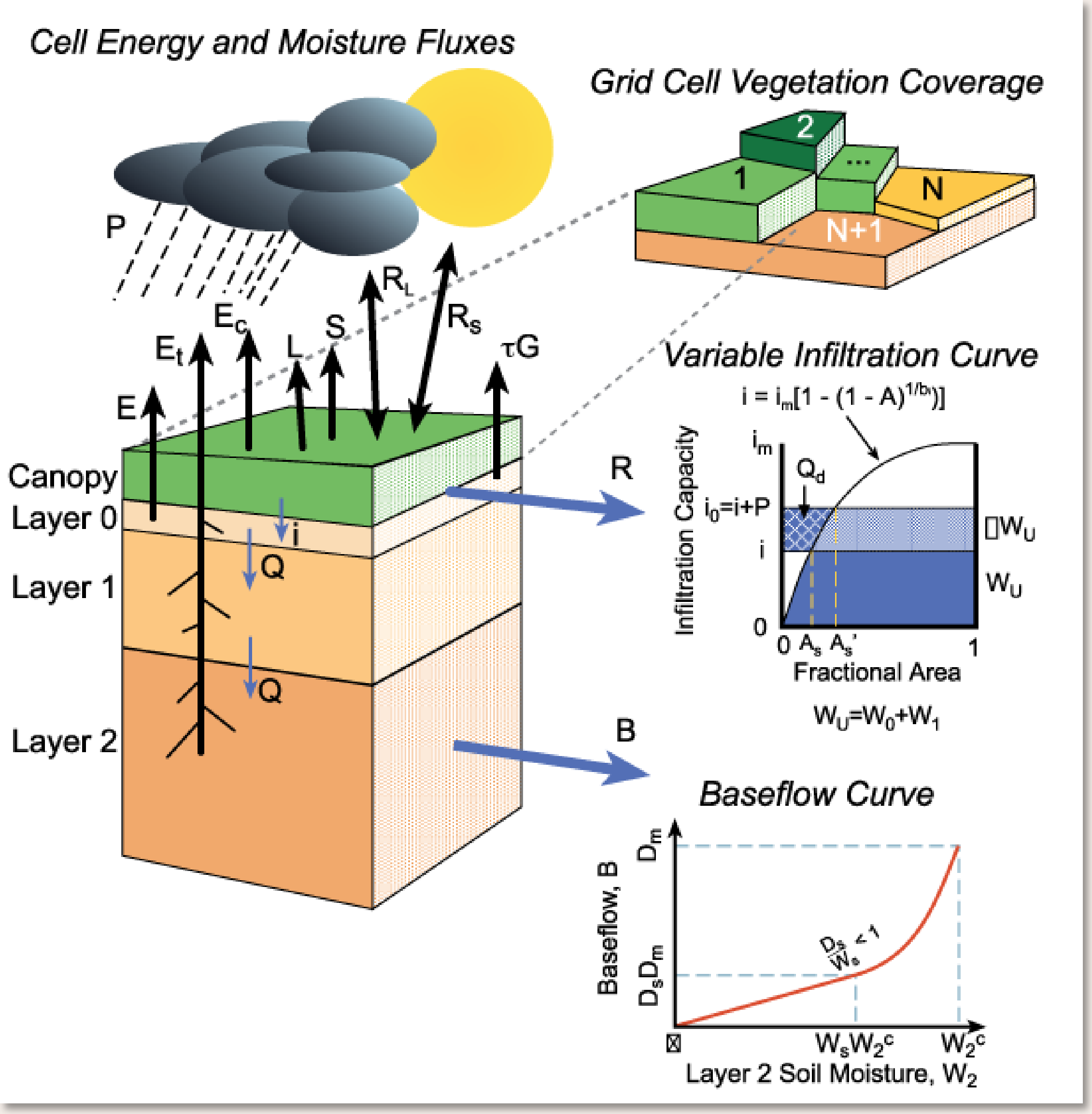


Figure 6.4

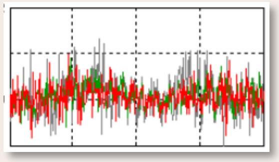
Schematic representation of the VIC model, showing land cover tiles, soil column, and major water and energy fluxes (Source: VIC Model Overview, https://vic.readthedocs.io/en/master/Overview/ModelOverview/)

models in that the states, inputs, and outputs are designed to emulate physical processes more explicitly (Figure 6.4).

LSMs use physical equations and other quantitative methods to simulate the exchange of water and energy fluxes at the Earth surface–atmosphere interface. For example, LSMs dynamically calculate potential ET (PET) and simulate evaporative fluxes through parametrizations of sub-processes such as vegetation transpiration and bare soil evaporation, while conceptual models may lack a representation of vegetation entirely, or take PET as an input or use PET as a parameter that is tuned in calibration.

Since their advent in the 1990s, VIC and similar land surface models have demonstrated their utility for a broader range of hydrologic analyses, including the assessment of long-term trends in regional hydrology (Mote et al. 2005), drought (Andreadis et al. 2005), streamflow forecasting (Hamlet and Lettenmaier 1999; Wood et al. 2002), climate change detection and attribution studies (e.g., Barnett et al. 2008) and impact assessment. In the Colorado River Basin alone, as discussed in Chapter 11, VIC has been used for at least a half dozen studies and is the basis for the major climate change hydrology datasets developed by a Reclamation-led consortium and archived at the Lawrence Livermore National Laboratory website. See section 6.3 for a more detailed description of the VIC model.

Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections



Link:
https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html

As alluded to earlier, VIC has parameters directly regulating the subsurface stores of water and the transfer (fluxes) of water from one storage layer to another. For soil drainage, where a conceptual model might apply a linear reservoir formulation in which the outflow from one bucket to the next is linearly related to the bucket's current water storage, a land surface model such as VIC represents water storage and transfer in terms of process concepts and attempts to specify parameters using observed, or estimated, geophysical attributes.

In a land surface model, soil drainage in the saturated zone may be described by a Darcy's law representation in which drainage rate is dependent on the amount of water in the column and a hydraulic conductivity parameter that is estimated based on the soil texture. However, because soil textures are very sparsely observed, the relationship between soil textures and the conductivity parameter are uncertain, and soil drainage is simulated at a spatial scale (e.g., 12 km) that is much larger than the scale at which the drainage process acts, this physically based model parameterization may be almost as rough an approximation of the real-world process as found in the conceptual model formulation. The hydraulic conductivity, soil layer depths and other physical parameters may also be used as calibration parameters, meaning that the soil drainage process in a physically based land surface model application may effectively be as "tuned" as the water transfer in a conceptual model. The greater process realism in the land surface model (or any physical model) and its distributed nature requires a far larger number of sensitive parameters—many of which may be hidden in the code through hardwiring (Mendoza et al. 2015)—and more complex model structure. The result can often be a model that is less amenable to calibration, that is, less flexible for tuning to reproduce observed variability for an output such as streamflow.

Table 6.1 provides a summary of the advantages, disadvantages and applications of stand-alone LSMs used in the Colorado River Basin. Figure 6.5 shows an example of VIC model output.

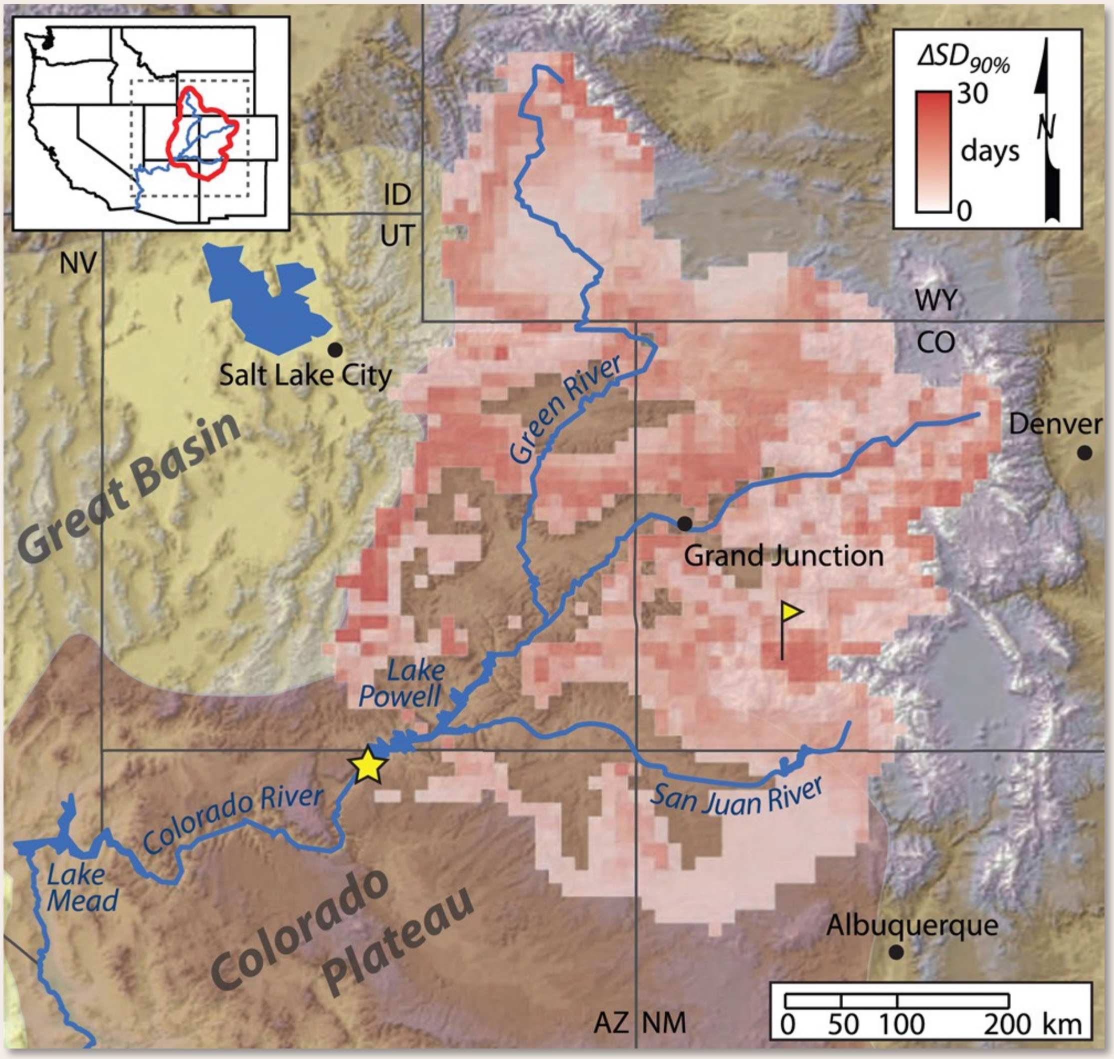


Figure 6.5

Example of output from an application of the VIC model in the Colorado River Basin. The red shading shows the mean difference per cell in the timing of snow depletion (ΔSD90%, i.e., the change in the date at which 10% of the peak snowpack remains) between 'Before Dust Loading' and 'After Dust Loading scenarios' for 1916–2003. (Source: Painter et al. 2010)

Land surface models (LSMs) in a coupled system

Over the last few decades, the land surface has become an increasingly well represented component in climate models. A GCM (from "General Circulation Model" or "Global Climate Model") is a modeling framework that couples a global atmospheric model, an ocean model, a sea ice model, and a land surface model (see Chapter 11). An Earth System Model (ESM) extends a GCM to include a suite of more detailed sub-models, including representations of the biogeochemistry of the ocean and land (e.g., carbon cycle, nutrient cycle, etc.), atmospheric chemistry, dynamic ice sheets (Lenaerts et al. 2019), dynamic vegetation, and water management.

Recently, computing capabilities have advanced such that more complex land surface schemes are being included in coupled GCMs and ESMs. Land surface models such as the NCAR Community Land Model (CLM) now incorporate detailed physics to represent land surface moisture and energy fluxes (e.g., the impacts of surface albedo on longwave and shortwave radiation), including the influence of land cover changes and idealized hillslope-scale effects on moisture distribution (Figure 6.6). Although these models are still run at a relatively coarse resolution (e.g., >25 km), some have more detailed parameterizations than a typical hydrology model like VIC, and far more detailed process descriptions than are found in conceptual models. This additional detail allows representation of processes such as vegetation dynamics and carbon-cycle physics that are key feedbacks into the climate system.

A long-sought objective for hydrologic science is to bring about a convergence in modeling so that local scale hydrology can be simulated by GCMs and ESMs, negating the need for calibrated stand-alone hydrology models like VIC (Fan et al. 2019). Lehner et al. (2019) provide a detailed perspective on the limitations of current (CMIP5) land surface models within GCMs to simulate runoff and runoff sensitivities in the Upper Basin (see Chapter 11). NCAR is currently developing a potential successor to the Community Land Model called the Community Terrestrial Systems Model (CTSM) that will ultimately be a more complete land model, including anthropogenic impairments (i.e., water management and irrigation at a coarse scale), and may soon have test case implementations that are usable for hydrologic applications related to water management.

The Weather Research and Forecasting Hydrologic modeling system (WRF-Hydro) used by the National Water Model (NWM; see section 6.3) is an outgrowth of both process-oriented watershed modeling and developments in the field of earth system modeling. In principle, WRF-Hydro can couple a land-surface model (primarily Noah-MP), a weather research and forecast model (WRF), a terrain routing model, a groundwater bucket model, and channel routing. However, WRF-Hydro in the NWM implementation is not actually coupled with WRF.

The last decade has also seen the rise of operational global domain models that are used for hydrologic analysis and prediction. Two operational forecasting centers, the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Swedish Meteorological and Hydrologic Institute (SMHI), are now producing naturalized seasonal hydrologic runoff forecasts for continental to global domains (Wetterhall and Di Giuseppe 2018; Emerton et al. 2018). Deltares, a research institute in the Netherlands, also runs a global, grid-based model for medium range ensemble forecasting in a system called the Global Flood Forecast Information System (GLOFFIS). It is now straightforward for large-scale modeling centers to link land surface and routing models to provide up-to-global scale hydrologic simulations. For instance, NCAR recently linked CLM runoff output with the MizuRoute channel routing model (Mizukami et al. 2016) to simulate streamflow for all of North America (Figure 6.7). NASA and other agency partners run the Famine Early Warning System (FEWS), which is based on global LSM applications, and universities such as Princeton and the University of Washington have run various LSM-based forecasting systems (e.g., with VIC) for over 15 years.

These continental to global efforts are all still in the initial stages. Their skill remains relatively unexplored and is often quite poor, yet it is worth noting them as a possible harbinger of future information resources and development. It is also possible that their forecasted natural runoff anomalies (e.g., percent of average) may be informative; they are driven by good quality weather and climate forecasts and could in some cases provide useful information in spite of model bias. The poor forecast quality is likely to improve in the future given that these modeling efforts are often tied to sizeable research and development resources and bring to bear high quality datasets and techniques that may not have been adopted in local scale forecasting. Many of them also are linked to long, consistent hindcasts that enable users to gage their skill and even bias-correct them, something that is unavailable in NWS real-time streamflow forecasts. Their current potential is likely to lie more in medium-range and seasonal (mid-range) forecasting, with short-range predictions from tailored, more local systems being relatively more actionable.

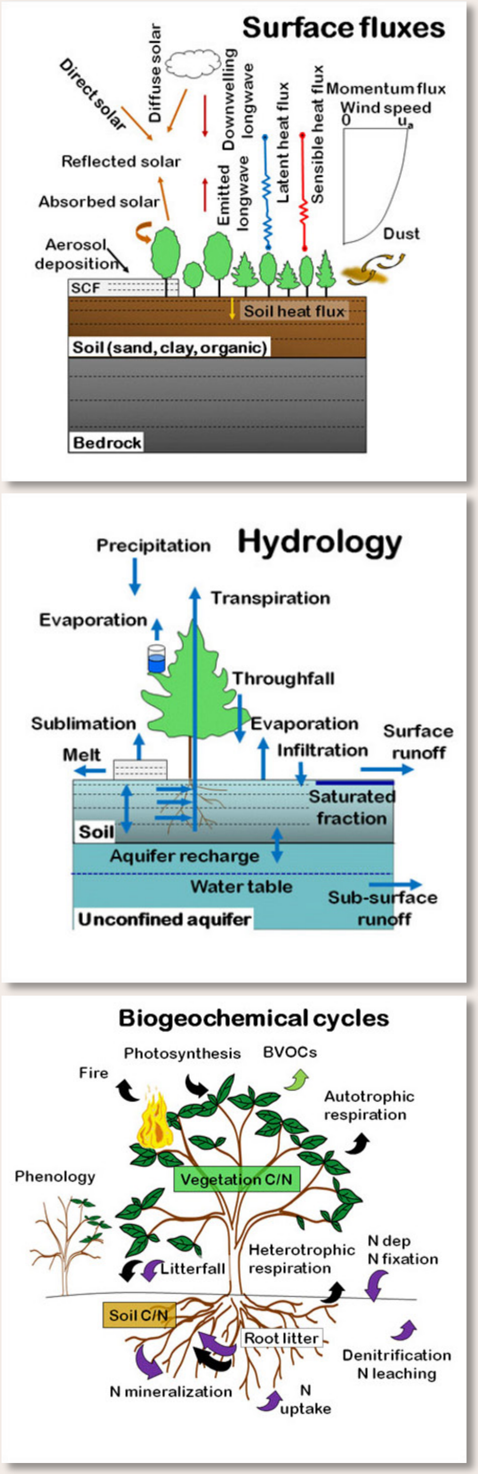


Figure 6.6

Schematic of the structural and physical characteristics of the Community Land Model (Source: "Community Land Model" http://www.cesm.ucar.edu/models/clm/)

Explicit watershed process models

Models applied within the discipline of fine-scale watershed science, which are often linked with intensively instrumented watershed observing networks, attempt to resolve watershed and hillslope-scale processes—interception, throughfall, myriad snow processes, infiltration, and vertical and lateral flow in saturated and unsaturated soils—in as much explicit detail as possible. Examples of such models include Gridded Surface/Subsurface Hydrologic Analysis (GSSHA), the Distributed Hydrology Soil Vegetation Model (DHSVM) (Figure 6.8), and the terrain-routing model included in the WRF-Hydro system.

A defining feature of the explicit watershed process model is the use of terrain gradients to drive lateral fluxes of water both overland and through the soil column, so that the runoff generation mechanism accounts not just for vertical fluxes of moisture but also the role of the landscape in distributing moisture horizontally, which is not represented in other types of models. In such models, groundwater can emerge at the surface at a break in grade, can flow downhill overland or within a fine-scale channel network, and then re-infiltrate the soil. In contrast, land surface models such as the VIC model, have simpler runoff-generation mechanisms, motivated by the assumption that the lateral fluxes of water between grid cells are much smaller than transport in channels (e.g., streamflow) and the vertical fluxes of ET and drainage. Table 6.1 provides a summary of the advantages, disadvantages and applications of explicit watershed process models used in the Colorado River Basin. Figure 6.9 shows an example of DHSVM model output.

Some watershed process models have distributed snow algorithms that allow for blowing and drifting effects caused by terrain and forcing variations. Because the models resolve vegetation almost down to the scale of an individual tree (about 10 m), or at least at the scale of a forest stand (about 100 m), the role of local vegetation in the hydrologic cycle is often explicitly represented, and described by many parameters. In fact, the development of DHSVM was motivated by an interest in quantifying forest harvest effects on runoff, including the impacts of individual roads and culverts.

The scale of such models is still far coarser than the scale at which processes such as soil infiltration occur (Clark et al. 2017; Seyfried and Wilcox 1995), thus like land surface models they are in some measure a conceptual representation, but their process orientation is still clearly greater than land surface models.

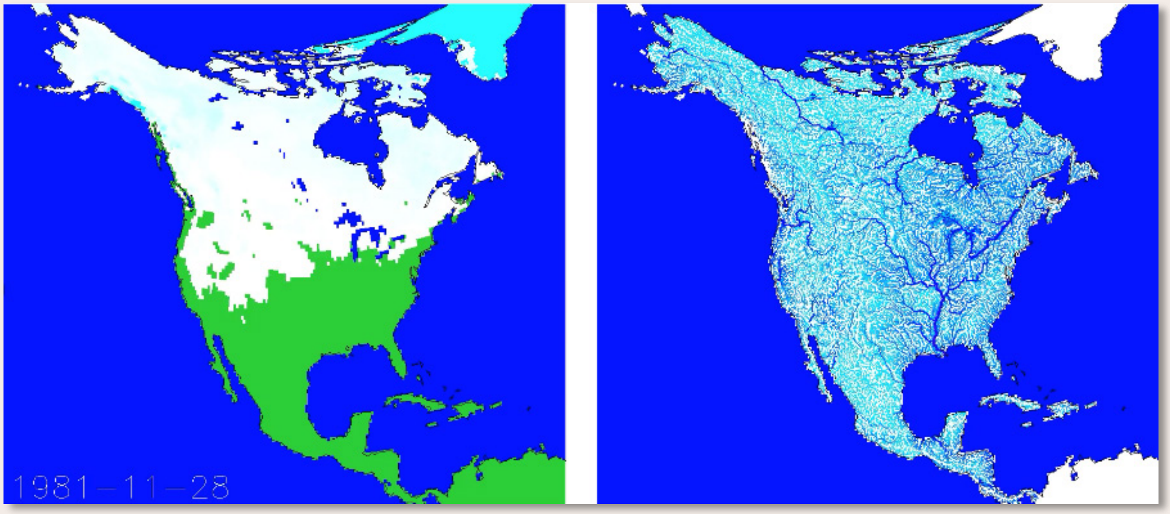


Figure 6.7

The convergence of continental-scale land surface modeling with streamflow simulation at watershed scales is illustrated by the coupling of a gridded CLM-based land model, illustrated by its SWE output (left), to a reach-based channel routing model (Mizuroute) implemented across North America to obtain streamflow (right). (Source: N. Mizukami and M. Clark, http://www.cesm.ucar.edu/events/wg-meetings/2019/lmbwg.html)

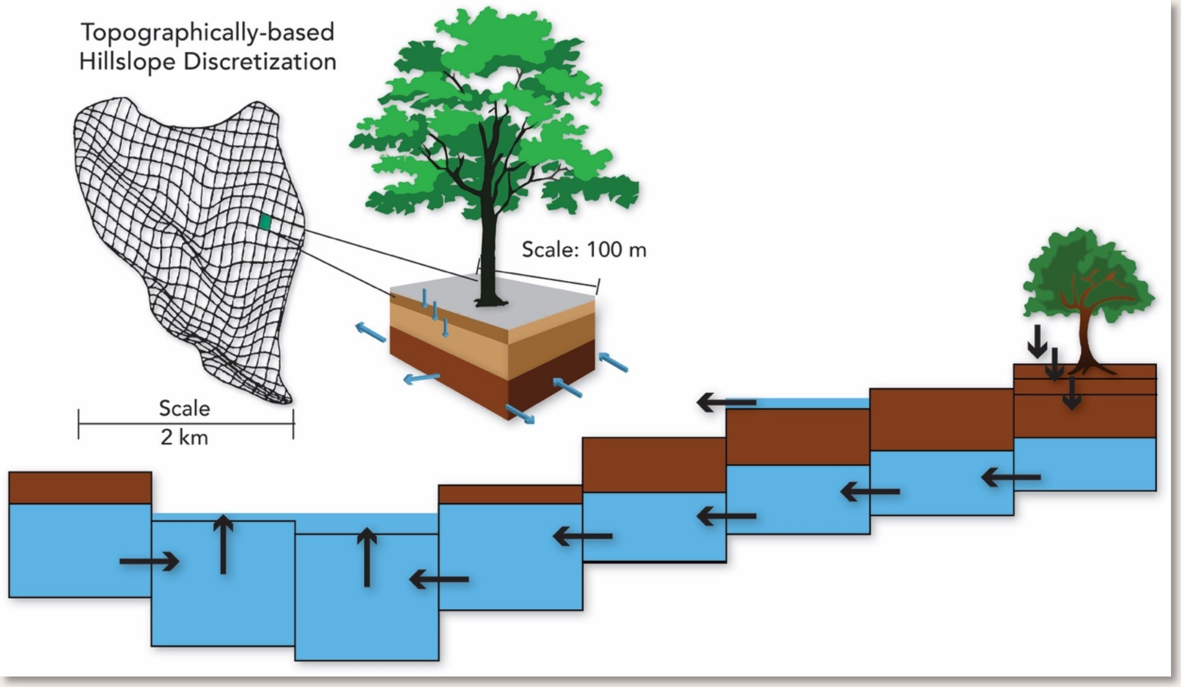


Figure 6.8

DHSVM model representation. (Source: adapted from Wigmosta, Vail, and Lettenmaier 1994)

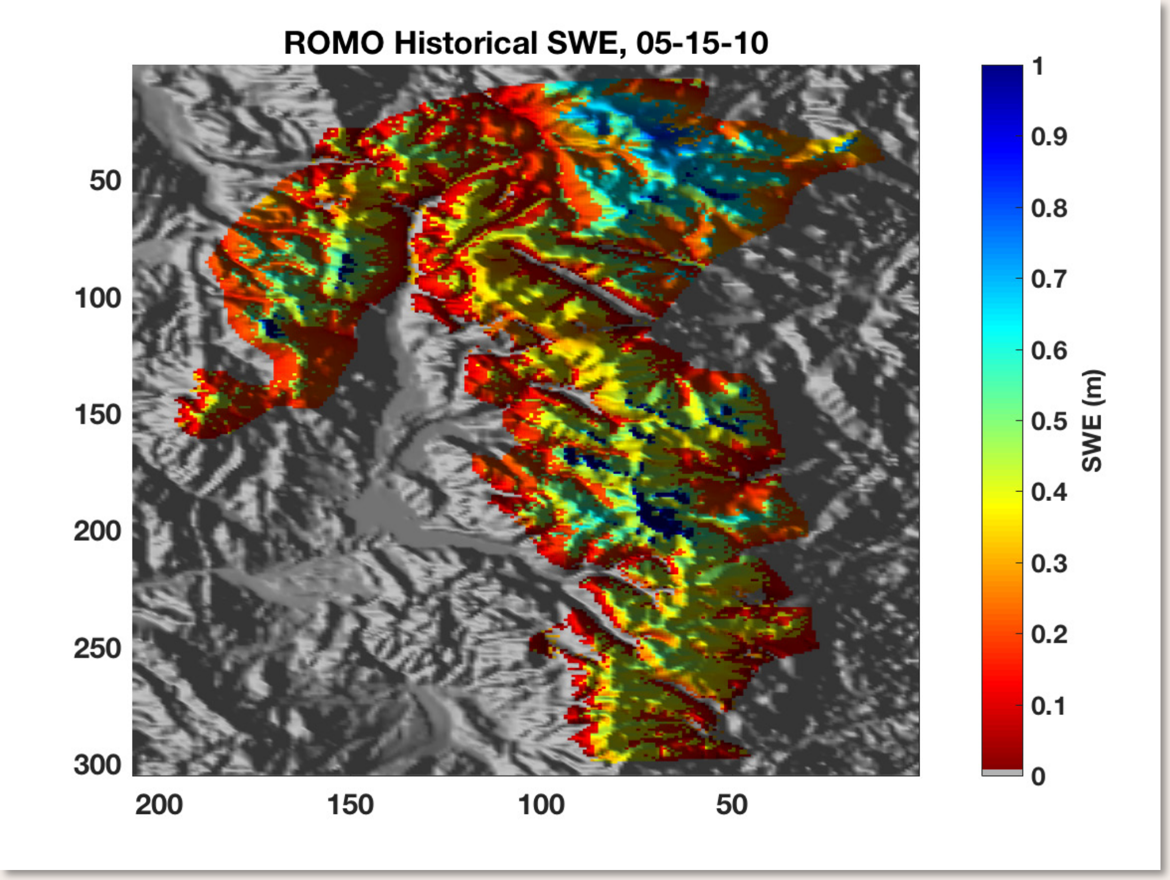


Figure 6.9

Example model output of DHSVM, showing simulated SWE for May 15th at a 250-m resolution, given observed historical temperature and precipitation data. The modeled area includes drainages in and near Rocky Mountain National Park. (Source: Aaron Heldmyer, CIRES)

Most applications of high-resolution explicit process models have been to support the investigation of geophysical questions in watershed science and ecology, including understanding the effects of beetle kill, juniper control strategies, forest thinning approaches, dust-on-snow phenomena, deglaciation, and groundwater-surface water interactions, among other topics. Until recently, it had been rare to find such models used in water resources applications such as streamflow forecasting or long-term climate change studies. In the U.S., Westrick, Storck, and Mass (2002) implemented a 150-m DHSVM model for streamflow prediction in the Pacific Northwest. More recently and notably, NOAA NWS launched the NWM for streamflow forecasting which coupled a 1-km resolution implementation of the Noah-Multiparameterization Land Surface Model (Noah-MP; Niu et al. 2011) to a 250-m terrain routing scheme (Gochis, Yu, and Yates 2015). See section 6.3 for a more detailed description of the NWM.

The use of such computationally intensive models for real-time forecasting as well as for geophysical process studies is enabled through advances in high-to-hyper resolution imagery, inexpensive supercomputing, broadband connectivity, and petabyte-scale data storage. Nonetheless, this technological progress is not quite adequate to make high-resolution (10–500 m) process-oriented models attractive (or feasible) for large-scale regional applications and long-range predictions or projections. The need to estimate model parameters at such fine scales and over large domains remains a scientific challenge that is not alleviated by more explicit spatial resolution or more complex physical parametrizations. While some hydrometeorological dynamics can be better captured by such schemes (such as terrain impacts on snow deposition), the need to calibrate many other parameters in a more unwieldy model is a major obstacle to achieving improved simulations.

New and emerging modeling approaches

In addition to the aforementioned hydrologic model types already used in the Colorado River Basin, there are several new modeling efforts underway that are still in early stages of development. These efforts focus on providing streamflow simulations. One is an application of the current NWM long-range configuration on a HUC12 catchment basis, which could offer a less computationally intensive and more calibratable model for mid-range (seasonal) Ensemble Streamflow Prediction (ESP). Another is the application of the Structure for Unifying Multiple Modeling Alternatives (SUMMA; Clark et al. 2015a, 2015b), also on a watershed HUC12 basis, for the entire U.S. as well as the Reclamation western U.S. management domain. A third is a research effort to integrate an energy balance snow model into RFC operational use, coupled with an 800-m Hydrologic Laboratory-Research Distributed Hydrologic Model (HL-RDHM) implementation. This effort was a NASA-funded collaboration between the CBRFC, Utah State University, and Riverside Technologies, Inc. (RTI, Fort Collins).

A very rapidly emerging modeling approach is the use of machine learning methods (e.g., neural networks) to produce watershed model simulations trained only on observed datasets, without any explicit representation of physical processes within the model. Since the machine learning modeling approach has been primarily applied to forecasting, it is discussed in more detail in Chapter 8.

Selecting appropriate models for different applications

As is shown in Table 6.1, different model classes and individual models have different characteristics and inherent advantages and disadvantages. Therefore, it is important to carefully articulate the modeling objectives, as well as the requirements a model must satisfy, prior to selecting a certain type of model. The limitations of data availability, time, and budget need to be identified to narrow the choices and select the appropriate model for the intended purpose (Sitterson et al. 2017). In practice, the need to identify all these different aspects is rarely met or even recognized. More often, a model is chosen for an attribute that may appear desirable for one objective, but greatly limits its potential to satisfy another objective. For example, the desire to implement, in the NWM, a model with a "street-scale" resolution led to an implementation that is not well suited for seasonal forecasting. In the case of the monthly calibrated VIC model, a desire to understand and project climate sensitivities is pushing increasingly beyond the capacity of the VIC physics to provide the required physical fidelity.

Despite recent interest in the idea of a "seamless" modeling approach that can, in principle, satisfy every use case, it is unclear that this is possible or desirable as a strategy for achieving multiple objectives optimally, let alone all possible objectives of interest to a water manager.

6.2 Model applications in the Colorado River Basin

Forecasting

The most well-known hydrologic modeling activities in the Colorado River Basin, and the most critical to water management, are the use of NWS models (e.g., Sac-SMA) within the Community Hydrologic Prediction System (CHPS) operational platform. They are used to produce real-time, single-value flood forecasts (out to 10 days lead time in most cases) and seasonal (mid-range) ensemble forecasts via ESP techniques (explained in Chapter 8). In addition, the NWS HL-RHDM is now being used by the CBRFC in an effort to experiment with distributed modeling and snow data assimilation for forecasting in the Upper Basin.

Although not originally designed for forecasting purposes, the VIC model has also been used in a number of research and quasi-operational forecast studies in the Colorado River Basin, run at 1/8th degree (12 km) and used to simulate streamflows at daily time steps at several dozen locations with medium-sized to large drainages (3,000–500,000 km^2) upstream. The focus of the VIC-based forecast effort has always been on seasonal streamflows and addressing questions about the potential value of seasonal climate forecast information (Wood, Kumar, and Lettenmaier 2005). Models arising from research efforts at the University of Washington in the 2000s were typically calibrated, using either manual or automated objective methods, to the naturalized streamflow dataset from Reclamation, much of which is at a monthly time step (Chapter 5). More recently, researchers at Los Alamos National Lab have recalibrated VIC at 1/16th degree (6 km), but that model has not yet been applied to forecasting.

Climate change impact projection and assessment

In the key locations used by Reclamation for management of the Colorado River Basin—i.e., larger headwater and tributary basins and mainstem locations—and at monthly scales, VIC's performance has been adequate to support long-range climate change impact assessments as well as mid-range ensemble streamflow prediction. The 1/8th degree VIC's greater process orientation (compared to the NWS models) has made it more acceptable for climate change studies, but there are also many ways in which VIC's physics are limited, and may not capture important dynamics that could alter projected hydrologic outcomes. These include surface water-groundwater interactions, dust-on-snow effects, dynamic vegetation influences, sub-grid variability in meteorological variables, and near-surface land-atmosphere feedbacks. Among the land surface models, VIC has dominated the usage for climate change impact assessment, becoming a *de facto* standard for the basin (see Table 11.4).

The NWS models have also been used for climate change impact assessment in the basin (e.g., Miller et al. 2011; 2012; 2013; Woodbury et al. 2012; Bardsley et al. 2013). However, because they lack an explicit energy balance, the NWS models are not as inherently suited as VIC for simulation of conditions beyond the envelope of weather and climate to which the models have been exposed in calibration and operational use. For example, for the studies cited above, the fixed monthly cycle of potential evapotranspiration (PET) had to be replaced with a dynamic PET representation based only on temperature change, lacking the other factors that influence PET such as solar radiation, humidity, and wind.

Some climate change studies extend beyond the quantification of climate change impacts to focus also on the statistical detection of hydrologic impacts and attribution to anthropogenically forced climate change. The VIC model has been applied to such detection and attribution studies, including for the western U.S. and the Colorado River Basin (e.g., Barnett et al. 2008; Pierce et al. 2008). The VIC model developed for the Colorado River Basin and run at 1/8th degree has also provided good research-quality naturalized flow simulations in various implementations for many analyses and studies over the past 15 years. Calibration to monthly naturalized flows has meant that their daily flow simulation, and simulation for basins for which they were not directly calibrated, is less optimized and substantially poorer than what is provided by NWS models like those used by the CBRFC. A gradual evolution of the VIC code, without accompanying recalibration, has also led to a degradation in model simulation quality.

Sensitivity studies

An increasingly active model application in the Colorado River Basin is sensitivity analysis—introduced in Chapter 2—which involves exploring observed trends and variability in basin hydrology and attempting to quantify their sensitivity to temperature, precipitation, and other climate factors. Sensitivity studies are important because they can provide a shorthand strategy for gauging the potential impacts of climate change on a basin's hydrology, and consequently water resources. Sensitivity analyses have been based on observations from the historical record as well as on paleo datasets, and on hydrologic models.

While observations are seen as reliable because their measurement accuracy and uncertainties are relatively well understood, models are attractive because they enable a controlled testing of the sensitivities of natural processes such as runoff generation through strategies like perturbing input meteorology; e.g., assessing the impact of a 10% decline in precipitation. The major drawback of models in this context is that they rely on the assumption that the model faithfully represents key watershed processes and their linkages to the independent variables of interest. While an integrated model output variable such as streamflow can be easily validated against observations, and errors in inputs may be indirectly estimated, it is rare that the sensitivities of intermediate sub-processes, such as infiltration or sublimation, and their completeness (e.g., whether all controlling processes are incorporated in the model) are evaluated and confirmed as being realistic. Consequently, model-based sensitivity analyses are inevitably dependent on the partially assessed fidelity of the model. Currently, the CBRFC is working on an accuracy assessment and sensitivity analysis of hydroclimatic parameters within the CBRFC modeling framework. The goal of this work is to improve the accuracy of the CBRFC's water supply forecast.

The primary models that have been used in sensitivity studies for the basin are all LSMs, with the VIC model being the most frequently used (Vano, Das, and Lettenmaier 2012; Vano and Lettenmaier 2014; Vano et al. 2014; Xiao, Udall, and Lettenmaier 2018). Among these sensitivity studies, Vano, Das, and Lettenmaier (2012) and Vano et al. (2014) also examined the output of other LSMs—CLM, Catchment, and Noah—as well as Sac-SMA. The latter of these two studies also looked at another conceptual model, the Simple Water-Balance Model presented by McCabe and Markstrom (2007), which had previously been used to model Colorado River Basin water supply risk (McCabe and Wolock 2007). As the name suggests, this model has a much simpler formulation of watershed processes compared to the other models discussed in this chapter. For example, the occurrence of snow is determined by precipitation falling below a mean monthly temperature threshold, which is a calibrated parameter. The model's ET is dependent on water availability and driven by Thornthwaite estimates of PET, which are sensitive to temperature but not radiation. It should be noted that the monthly time step of this model increases uncertainties considerably due to averaging of inputs and outputs that are often nonlinear.

6.3 Descriptions of key hydrologic models relevant to the basin

In the Colorado River Basin, the most frequently consulted hydrologic models have been the NWS models (Sac-SMA and SNOW-17) for streamflow forecasting, and the VIC model for sensitivity studies and climate-change projections of hydrology. These models also exemplify their respective broader classes of models (conceptual models and land surface models) as summarized in Section 6.1. Below are extended descriptions of these two models, their setup and use, and calibration and inputs. The National Water Model (i.e., WRF-Hydro and other components) is also described, even though it is not (yet) in operational use in the basin, because it represents recent trends and new methods in hydrologic modeling, and because NOAA intends for it to become the operational model for the NWS RFCs, including the CBRFC, in the future.

National Weather Service models

In the 1970s, the National Weather Service began developing the River Forecast System (NWSRFS), a collection of interrelated software and data capable of performing a wide variety of hydrologic and hydraulic functions. The primary hydrology model deployed within NWSRFS was actually two models: Sac-SMA for modeling precipitation-runoff processes, and SNOW-17 for modeling snow accumulation and ablation. Other models developed for use within NWSRFS accounted for agricultural water use, conversion of runoff volume into instantaneous discharge (i.e., unit hydrograph implementation), reservoir operations, and other hydrologic processes. In 2012, most of the legacy hydrologic models and other software of NWSRFS, including Sac-SMA and SNOW-17, were migrated into a new software platform, the Community Hydrologic Prediction System (CHPS).

CHPS is an interactive platform that specifies models and operations within a workflow to run both short-range streamflow and flood forecasts and seasonal (mid-range) ensemble streamflow prediction (ESP) forecasts. CHPS is the NWS implementation of the Delft-FEWS software platform. Since its deployment at the CBRFC and the other RFCs beginning in the early 2010s, CHPS has provided greatly increased interactivity and flexibility to the forecast centers in incorporating and visualizing data and constructing modeling and forecasting workflows.

Sacramento-Soil Moisture Accounting Model (Sac-SMA)

Sac-SMA is a lumped conceptual model that attempts to represent soil moisture characteristics to effectively simulate runoff that may be subsequently routed to become streamflow (Figure 6.2). Sac-SMA simulates six types of runoff, which can be further divided into fast- and slow-responding processes. In fast-responding processes, surface runoff is routed to a channel within hours and is typically driven by rainfall or snowmelt events. Runoff that is characterized as fast-responding includes intensity-dependent surface runoff (i.e., runoff or snowmelt that exceeds the infiltration rate of unsaturated soils), runoff from impervious areas, and direct runoff (i.e., runoff after soils reach saturation). Slow-responding processes occur over porous areas and account for interflow, supplemental baseflow (e.g., water that drains from soils up to two months after an event), and primary baseflow (e.g., water that drains from soils over the course of years and sustains perennial flow during dry periods).

Within Sac-SMA, the soil is represented by two vertical zones to capture soil moisture processes near the surface as well as groundwater processes deeper within the soil column. Soil moisture within the upper zone is influenced by fast-response processes, and lower zone soil moisture is influenced by slow-response processes. Water can be stored and exchanged between the two soil zones; if the volume of water input to the model exceeds the modeled soil capacity, or if the rate of water input exceeds transport rates defined in the model, then water is available to the channel as runoff.

Sac-SMA model parameters are determined through calibration (see below) and define several quantities of the Sac-SMA's conceptual representation of physical soil processes. Among the parameters are the size and rate of soil moisture zones and transport, the percentage of water destined for deep aquifer storage, and land cover characteristics such as the impervious nature of an area, or amount of area covered by riparian vegetation.

Simulated soil moisture within the model can be characterized by tension or free water, and can be present in both lower and upper soil zones. Tension water may only be removed through evapotranspiration. Free water may be removed through evapotranspiration, percolation, and interflow. Lower-zone free water can be further characterized as supplemental or primary. Primary water drains slowly and describes baseflow over long periods of times, on the order of months to years. Supplemental water is more readily available to runoff than primary water and typically drains in the weeks to months following an event, augmenting primary baseflow. Each type of modeled soil moisture (tension, supplemental, and free) have defined maximum capacity values dictating how much water can be held at any given point.

Soil moisture transport rates are also defined through the model calibration process and determine how quickly water can move between zones and as interflow. Percolation is a function of lower zone dryness and upper zone free water content. The percolation rate influences how much water becomes surface runoff or interflow from the upper zone during a storm event and how much water is stored in the lower zone that can become available at a later time as baseflow.

SNOW-17

Since Sac-SMA effectively assumes that all precipitation reaches the surface as liquid water, a separate model is needed to represent snow and snowmelt for regions like the Colorado River Basin, in which snowmelt is an important component of overall runoff. SNOW-17, like Sac-SMA, is a lumped conceptual model that requires only precipitation and temperature to model snowpack accumulation and ablation. The model characterizes precipitation as rain or snow based on temperature and freezing level information and builds or melts a snowpack in response to these forcings. While the SNOW-17 model is relatively simplistic compared to models that rely on an energy balance and significantly more forcing data, it consistently performs well and often better than more complex snow energy-balance models (e.g., Franz, Hogue, and Sorooshian 2008).

Since temperature is used as a proxy for incoming solar radiation in SNOW-17, there are times when SNOW-17 may not melt snow at the rate observed. For instance, during cloudy warm days, the model may melt snow too quickly—in reality, cloud cover will inhibit incoming solar radiation, resulting in slower melting. When dust is covering snowpack (i.e., dust-on-snow conditions), the rate of modeled snowmelt may be too slow—in reality, the lower snow albedo results in the increased absorption of solar energy and quicker melt. In operations, such model inaccuracies may be corrected through adjustments to model parameters such as the melt factor.

Other snow-related products used by the CBRFC, and the snow simulation itself, are described further in Chapter 5.

Model setup and general use

The modeling units in CHPS consist of basins on the order of 10–1000 km^2. This allows for efficient calibration during the model development phase, and for examining and iteratively updating model forcings (e.g., temperature and precipitation data), states, and outputs in real time during the forecasting process. An example of this lumped approach is provided in Figure 6.10.

The primary models for an individual basin are SNOW-17 coupled to the Sac-SMA model, along with a routing function such as the Lag/K or unit hydrograph. The models embedded within CHPS provide a broad array of additional analytical and interactive functions, including model calibration, state updating, and post-processing, all accessible via an interactive interface.

The modeled Colorado River Basin is divided into about 400 basins, each having 1–3 elevation zones, which are simulated in a workflow that proceeds each day from the headwaters to the basin outlet, correcting obvious deficiencies in meteorological inputs and model behavior, basin by basin, and accounting for known and estimated impairments, including storage operations, diversions and consumptive uses. The Upper Basin and Lower Basin models are run at 6-hourly and 1-hourly time steps, respectively, with the latter reflecting the flashier hydrologic response times in the Lower Basin.

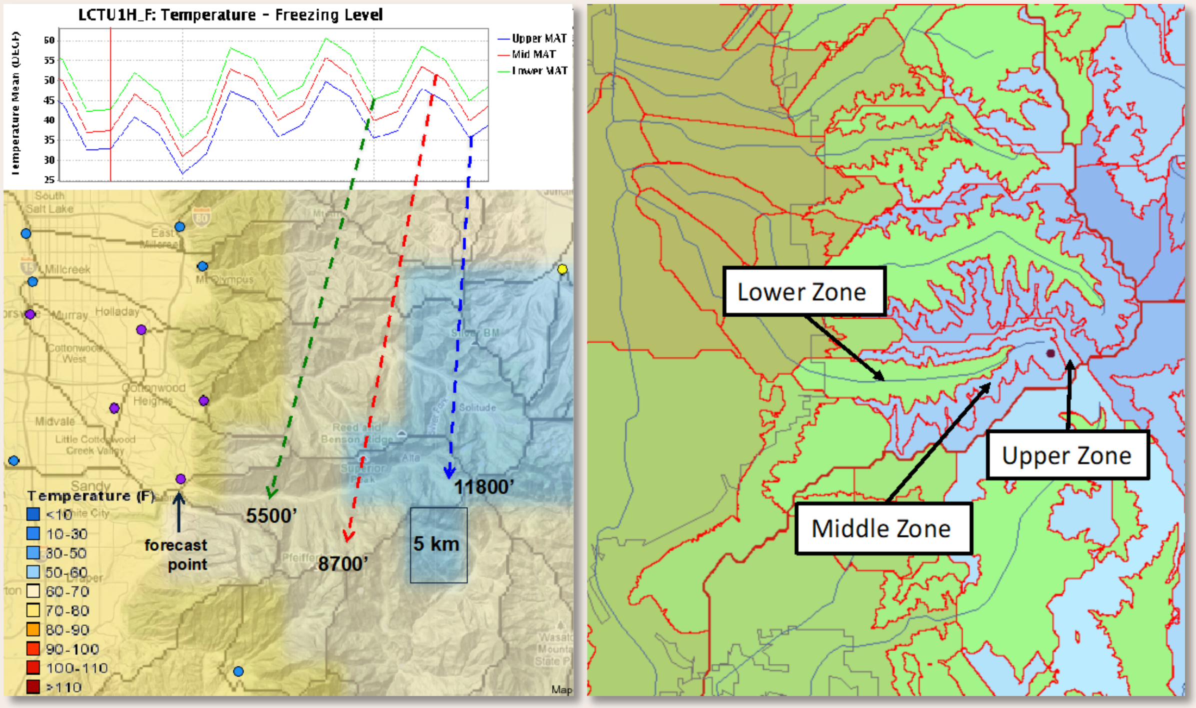


Figure 6.10

Illustration of the NWS traditional lumped approach to watershed modeling for the Little Cottonwood River canyon outside of Salt Lake City, Utah (right). The effect of elevation on temperature over the 6000+ foot terrain range is reflected in the mean areal 6-hour temperature forcings (left, top) that are developed for each of three elevation zones applied for the watershed of forecast point LCTU1 (right). Precipitation forcings and model parameters are also distinct for each zone. The elevation zones are not necessarily contiguous. A 5-km resolution gridded temperature analysis revealing similar gradients is shown for comparison (left, bottom). (Source: A. Wood, NCAR)

CHPS is designed for interactive use by forecasters. During critical times, forecasters use a myriad of methods to obtain data to enhance their awareness of the evolving dynamics in the basin, even beyond automated data systems. Phone calls to reservoir operators or to stream gauge operators such as the USGS can clear up any questions about measured flows, while intake of satellite snow information can inform snow cover fraction, and even viewing webcams of certain road locations can add insight about whether precipitation is falling as snow or rain at different locations. RFC forecasters use a combination of manual and automated techniques to correct input data, going beyond the scrutiny already given to that data by the source agencies.

The SNOW-17 and Sac-SMA models as implemented by RFCs are well-known for being highly calibrated, and they currently offer the best performance in simulating streamflow down to sub-daily time-scales. Their application in forecasting also contains the most comprehensive use of information about impairments to the natural hydrologic system, even while many uncertainties remain in those data (Chapter 5). The optimized, conceptual nature of the models, however, gives rise to concerns about their ability to represent both evolving climate and weather patterns, and to represent changes in land cover, such as from fires, dust-on-snow, beetle kill, or changes in the seasonality of vegetation due to warming. Depending on the scale of these landscape disturbances, changes to the model can be made to account for hydrologic impacts; for instance, after a large, severe, fire, the impervious area within a basin may be adjusted to simulate increased runoff due to the presence of hydrophobic soils. Their reliance on fixed PET (which is not required, but is the configuration in which they are implemented) argues against their use for long-term projection without modification to the PET scheme.

Calibration

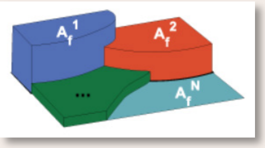
A long-standing and critical part of the RFC implementation of SNOW-17 and Sac-SMA has been model calibration. This includes extensive effort to develop or obtain records of impairments that affect streamflow, such as diversions and reservoir operations. Biases of no more than a few percent are common, and unlike other models used in the basin, calibrations are updated when forcings change (e.g., when the WMO climate normal period, currently 1981–2010, advances each decade), or more frequently. Some RFCs contract model calibration out to consulting companies such as RTI and more recently, Lynker, which have nationwide contracts with NWS that include this service.

Model calibration in the Colorado River Basin has been performed manually at the RFCs and for research studies, with the objective of minimizing errors in streamflow simulation. For the NWS models, observational datasets providing *a priori* parameters are the starting point (Koren, Smith, and Duan 2003; Anderson, Koren, and Reed 2006; Schaake et al. 2006). Algorithms for automated, objective parameter estimation have also long existed in the NWS calibration software in the form of the Shuffled Complex Evolution (SCE) single-objective optimization method (Duan, Sorooshian, and Gupta 1994). SCE usage in RFCs is mixed, however, with the general view being that it can provide an improvement over *a priori* parameters but does not perform so well that further manual tuning is not required. In recent decades, numerous parameter optimization algorithms have been introduced and are accessible in multi-method software packages such as Ostrich (Matott et al. 2013) but these are not yet used by the RFCs.

Variable Infiltration Capacity (VIC) model

VIC is a grid-based, macroscale, semi-distributed physical land surface model (LSM) that solves full water and energy balances. VIC was developed at the University of Washington (Liang et al. 1994), and in its various forms has been applied to most of the major river basins around the world. Development and maintenance of the current official version of the VIC model is led by the Computational Hydrology group in the Department of Civil and Environmental Engineering at the University of Washington. The VIC model is an open-source development project that is now in its 5th major version; every new application addresses new problems and conditions that the current model may not be able to handle, spurring further development and iteration. Further information on the VIC model is available on a website hosted by the University of Washington Computational Hydrology Group.

Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model



Link: https://vic.readthedocs.io/en/master/

Model setup

The VIC model is run at nominal grid resolution (e.g., 12-km or 1/8th degree dimension grid cells) but attempts to represent sub-grid variability in vegetation and elevation. VIC is regarded as a column model, which means that water cannot flow laterally, and the soil column in most applications is divided into three to five soil layers (Figure 6.4). Physical equations are used to simulate water and energy flows throughout the model. For example, evapotranspiration is calculated based on the Penman-Monteith equation (Penman 1948; Monteith 1965), soil drainage in the saturated zone is described by Darcy's law, and surface runoff in the upper soil layer is calculated based on the variable infiltration curve (Zhao et al. 1980). In addition to these processes, VIC simulates runoff in the upper surface layer and the release of baseflow from the lowest soil layer. Surface and base flow are subsequently routed by a separate routing model along the stream network to the basin outlet. Snow is represented in several forms: as a surface snow pack, as snow in the vegetation canopy, and as snow on top of lake ice when lakes are represented. More recently, VIC physics have been expanded to include ponded water, rudimentary glacier melt and migration, and frozen soils.

The land surface in VIC is modeled as a grid. VIC represents sub-grid variability in vegetation and elevation by partitioning each grid cell into multiple land cover and elevation classes. Inputs are sub-daily meteorological time series of air temperature, precipitation, radiation, and wind speed. Land-atmosphere interactions and water and energy balances at the surface are simulated at a daily or sub-daily time step. Water can only enter a grid cell via the atmosphere, and once water reaches the channel network, it is assumed to stay in the channel, i.e., it cannot flow back into the soil.

Calibration

Regional calibration remains a longstanding challenge in hydrologic modeling. The VIC models used in the Colorado River Basin are infrequently calibrated due to the expense. The last official calibration is believed to have occurred in 2004 (Christensen et al. 2004; J. Prairie, *pers. comm.*). In that study, VIC was calibrated on the Reclamation natural flows published at that time for three points in the basin: Green River at Green River, UT, Colorado River at Cisco, UT and Colorado River above Imperial, AZ.

Originally, the VIC models were calibrated manually as part of efforts to develop both climate change impact assessments (Christensen et al. 2004) and mid-range (seasonal) ensemble streamflow forecasting (see Chapter 8). The most recent calibrations were made using an automated multi-objective parameter estimation software package called MOCOM (Yapo, Gupta, and Sorooshian 1998).

Since the calibrations were last completed in the mid-2000s, the VIC model source code has evolved. In particular, the internal forcings-related code derived from MTCLIM (Running and Thornton 1996) has been upgraded. This code translates input of daily temperature minima and maxima, precipitation, and wind speed into sub-daily forcings for different elevation zones. These changes altered the simulated flow, in some cases by 20-30%, which is documented for locations included in the BCSD5 technical memo (Reclamation 2014).

The continued usage of VIC for water supply studies without sufficient effort to recalibrate and calibrate more extensively is a real concern, as a degraded calibration can significantly affect projected streamflow changes. Many of the basin studies conducted by Reclamation around the West have included new VIC calibration efforts, but not the Colorado River Basin Study (Reclamation 2012c). For the Colorado River Basin Study, a newer version of VIC was not recalibrated, though it was validated: it was run with historical climate to evaluate how well the new VIC version simulated the 29 natural flow points used by Reclamation (J. Prairie, *pers. comm.*). The results of this effort are published in Reclamation (2012c), page B4-3.

Model enhancements are typically developed by grant-funded projects in the small number of universities that have adopted VIC for hydrologic research. Like many models, VIC is not bug free and improves over time as bugs are found and fixed. As VIC versions change, and the forcings used to drive VIC are upgraded, the model itself is not always recalibrated to maintain streamflow simulation performance, which tends to degrade in the face of these changes. To support climate change work in the early 2010s, such as the CMIP3 hydrology projections effort, Reclamation assembled existing VIC model configurations and mosaicked them into a West-wide domain, but without significant recalibration (Reclamation 2011).

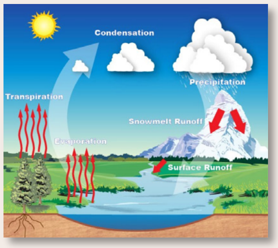
More recently, after the CMIP5 hydrology projection effort, Reclamation and the U.S. Army Corps of Engineers have funded research into improving VIC model regional calibration (e.g., Mizukami et al. 2017). One of the problems of the CMIP5 VIC modeling involved spatially distributed VIC parameters: parameter tuning done by each region results in patchy spatial artifacts that cause spatial patterns in the simulations. Mizukami et al. (2017) focused on testing a new Multiscale Parameter Regionalization (MPR; Samaniego, Kumar, and Attinger 2010) approach that had been successfully demonstrated for a different land surface model. The VIC MPR results did achieve seamless parameter fields (by design) versus a patchwork of individual basin parameter fields, but results often did not equal or exceed the individual basin calibrations. The simulations from this study are available, but not for further practical application (N. Mizukami, *pers. comm.*).

Simulation biases from models including, but not limited to, VIC has motivated new Reclamation projects to develop methods for bias correction of outputs—particularly streamflow—that may be required in order to provide a confident simulation under current and historical climate, against which future projections of streamflow can be evaluated. Because bias correction is often a prior step in climate downscaling, when applied to streamflow it is often referred to as secondary bias correction.

National Water Model (NWM)

The NOAA National Water Model, or NWM, is a next-generation hydrologic modeling and forecasting platform first launched in 2016. The NWM is notable because it represents a first attempt to implement very high resolution watershed process-oriented models for operational forecasting across the entire U.S., yielding forecast outputs on 2.7 million different stream and river reaches. The NWM is operated by the NOAA Office of Water Prediction at the National Water Center, with input and feedback from the RFCs regarding the skill and usability of forecast products. The NWM is the latest NWS-led foray into distributed modeling to supplant the Sac-SMA and Snow-17 models for operational streamflow forecasting, following the decade-long effort to introduce the coarser Hydrologic Laboratory-Research Distributed Hydrologic Model (HL-RDHM) in the RFCs.

National Water Model



Link: https://water.noaa.gov/about/nwm

Model setup and use

In the NWM, the water cycle is simulated with mathematical representations of the different processes in a river basin, and how these processes interact. The representation of these processes, such as infiltration, snowmelt and the flow of water through soil layers varies with changing soils, elevations, vegetation types and other variables. Simulations of the interactions and stream responses, which can change very quickly due to spatial and temporal variability in precipitation, must be run on a high-powered computer or super computer to support decision makers who need a fast turnaround when, for instance, flooding potential is high.

The NWM runs four uncoupled simulations of current conditions with look-back periods ranging from 28 hours to 3 hours. The initial conditions for the model's forecast runs are provided by these simulations or analyses. Short-range forecasts are executed hourly over the CONUS. The NWM produces hydrologic signaling at a very fine spatial and temporal scale. It complements official NWS river forecasts, which are at approximately 4000 locations across the CONUS, and produces guidance at millions of other locations that do not have a traditional river forecast. The NCAR-supported WRF-Hydro system is the core of the NWM. The Noah-MP land surface model (LSM) is used by WRF-Hydro to simulate land surface processes.

The NWM provides a number of forecast products, including products termed short-range (0–2 days), medium-range (0–10 days), and long-range (0–30 days). The short-range forecasts are deterministic single-value forecasts; the medium-range forecasts are from a 7-member ensemble; the long-range forecast is an ensemble updated daily, based on inputs from the NCEP CFSv2 climate forecast system (Chapter 7). The NWM relies on a 1-km resolution implementation of Noah-MP (Niu et al. 2011) coupled with a 250-m terrain routing scheme (Gochis, Yu, and Yates 2015), and a bucket groundwater model. Thus, given the model classification scheme in Table 6.1, the NWM is a hybrid of a land surface model and an explicit watershed process model, in terms of the detail of its physics and its spatial resolution.

The NWM contains orders of magnitude more complexity in its process description and spatial resolution than the NWS models, but has not been demonstrated to yield sufficient performance to be suitable for most applications of interest for water management in the Colorado River Basin, including short-range (1-10 day) and mid-range (seasonal) forecasts. Its heavy computational demands have also limited its ability to be directly calibrated, to provide seasonal water supply forecasts, especially in ensemble mode, and to be used for long-range projection. The NWM's optimal use at present appears to be flash-flood prediction, which benefits greatly from its ability to route streamflow through a high-resolution (250 m, 2.7 million-reach) channel network. The flash flooding application is less compromised by the deficiencies of the hydrologic simulation, because the intense rainfall rates and saturated hydrologic conditions lead to more straightforward rainfall-runoff relationships.

NWM calibration

The NWM was first implemented as an uncalibrated prediction system, but has since been subjected to several rounds of calibration effort. In contrast to the computationally cheaper VIC and RFS models, only parts of the NWM domain can be directly calibrated. Parameters are estimated using the Dynamically Dimensioned Search algorithm (Tolson and Shoemaker 2006) for small unimpaired basins and then distributed to the larger domain using concepts of ecological similarity. This approach has led to some improvement in NWM performance, but performance in basins not directly calibrated still lags considerably behind the NWS models.

6.4 Challenges and opportunities

Strong progress has been made over the last few decades in hydrologic modeling, including improved observations, scientific understanding, model process representations, and computing power and efficiency. In the Colorado River Basin, hydrologic modeling has primarily centered on the NWS models for operational short-range to mid-range (seasonal) forecasting, and the VIC land surface model for mid-range forecasting, trend and variability analysis, and climate change impact projection. These modeling capabilities under current practices have limits, and there are opportunities to advance beyond those limits, through improved meteorological inputs, better parameter estimation and calibration schemes, and development or adoption of new modeling platforms. These opportunities are summarized below.

Challenge

The conceptual modeling approach used in operational forecasting is not well-suited to take full advantage of advances in process understanding and modeling. The process-complexity of the models used for short-range to seasonal forecasting could be increased, albeit in a careful manner. This must be done within a strategy that acknowledges and provides for commensurate changes in operational workflows, including the development of data assimilation approaches.

Opportunity

- Implement a testbed framework for operational modeling that can incrementally advance and benchmark modeling improvements for different objectives, evaluating and justifying increases in complexity based on model performance.

Challenge

Distributed regional parameter estimation remains a vexing scientific challenge, and there is a critical need for accessible, efficient model calibration approaches to avoid the use of semi-calibrated land surface models in water supply applications (e.g., climate-change impact assessment). Without this capability, no model will perform well, and watershed-tuned conceptual models will be hard to outperform.

Opportunity

- Multiscale Parameter Regionalization (MPR) offers promise but will require more development to leverage both the strengths of the attribute-based parameter development and the greater optimization potential in individual basins. Improved understanding of parameter sensitivities in models such as VIC, multi-objective calibration (considering more variables than just streamflow), and broader use of geophysical attributes, may offer near-term paths for improvement.

Challenge

The widespread use of VIC and similar land surface models for climate change impact studies may have inadvertently limited the exploration and quantification of projected hydrologic changes (Chapter 11). There is a need to identify processes that are not represented in models such as VIC and that lead to hydrologic impacts that affect stakeholders (such as dust-on-snow, Chapter 5), and to require that models used in climate-change impact studies a) include parameterizations to represent those processes, and b) demonstrate that their process performance is realistic.

Opportunity

- New models and modeling frameworks such as SUMMA, Noah-MP, WRF-Hydro, and CTSM may offer a more flexible foundation for enhancing model process complexity in appropriate, and carefully benchmarked ways. Process parameterizations in individual models may be leveraged to expand the range of options in flexible model frameworks. This activity will ideally be deliberate, pursuing targeted model improvements and motivated by stakeholder needs assessments, rather than top-down or wholesale adoption of an alternate off-the-shelf model.

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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

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