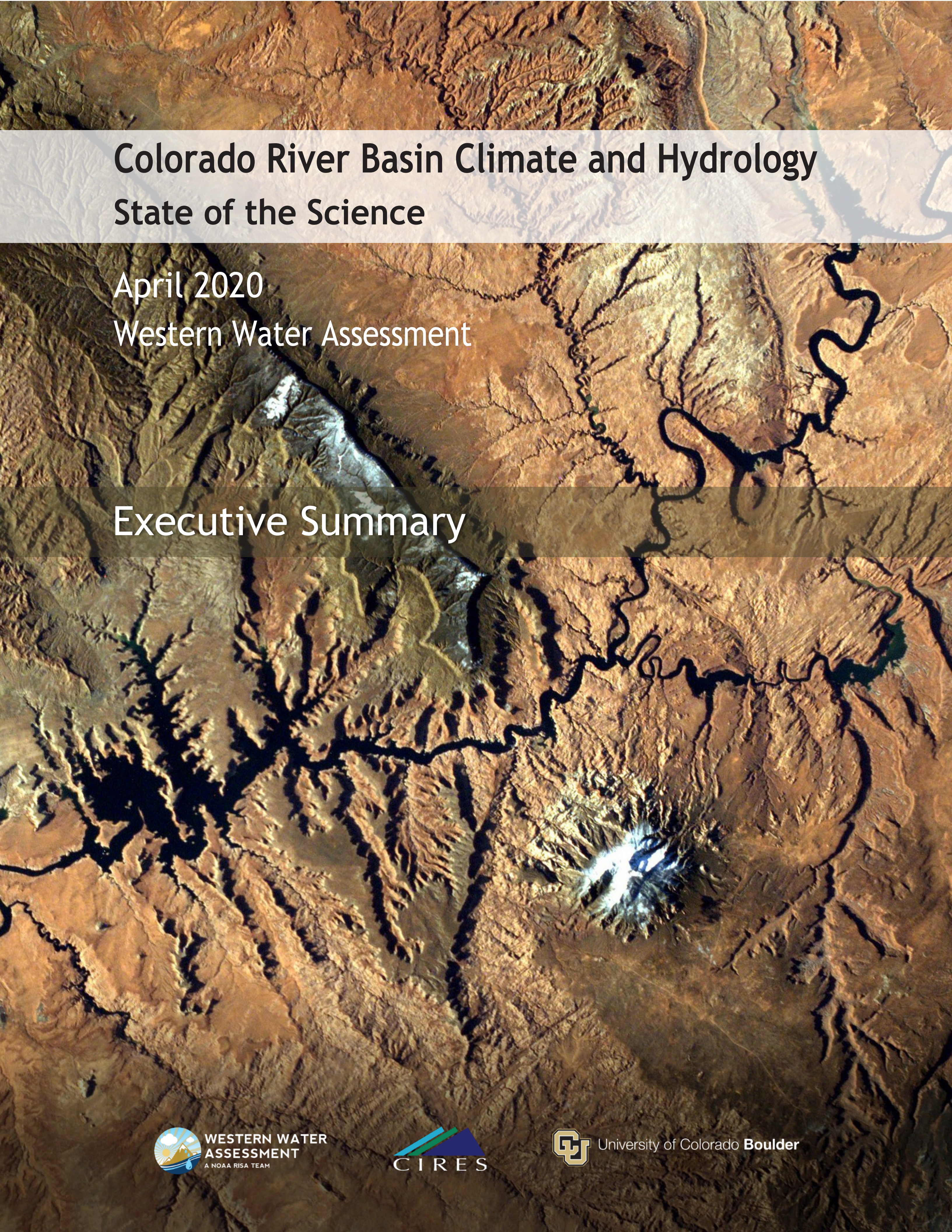

Colorado River Basin Climate and Hydrology

State of the Science

April 2020

Western Water Assessment

Executive Summary

WESTERN WATER ASSESSMENT
A NOAA RISA TEAM

CIRES

University of Colorado **Boulder**

Colorado River Basin Climate and Hydrology
State of the Science

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Editors and Lead Authors

Jeff Lukas, University of Colorado Boulder (CU Boulder), Cooperative Institute for Research in Environmental Sciences (CIRES), Western Water Assessment (WWA)

Elizabeth Payton, CU Boulder, CIRES, WWA

Authors

Stephanie McAfee, University of Nevada, Reno

Andy Wood, National Center for Atmospheric Research (NCAR) Research Applications Lab (RAL)

Connie Woodhouse, University of Arizona, Climate Assessment for the Southwest (CLIMAS)

Ben Harding, Lynker

Lineke Woelders, CU Boulder, CIRES, WWA

Rebecca Smith, Bureau of Reclamation, Lower Colorado Basin Region

Ethan Gutmann, NCAR RAL

Flavio Lehner, NCAR Climate & Global Dynamics Lab, and ETH Zürich

Joseph Barsugli, CU Boulder, CIRES, WWA

Klaus Wolter, CU Boulder, CIRES

Imtiaz Rangwala, CU Boulder, CIRES, WWA, and North Central Climate Adaptation Science Center

Benét Duncan, CU Boulder, CIRES, WWA

Jeff Deems, CU Boulder, CIRES, WWA, and National Snow and Ice Data Center (NSIDC)

Carly Jerla, Bureau of Reclamation, Lower Colorado Basin Region

James Prairie, Bureau of Reclamation, Upper Colorado Basin Region

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Technical reviewers

Chapter 2
Michael Crimmins, University of Arizona, CLIMAS
Russ Schumacher, Colorado State University, Colorado Climate Center
Brad Udall, Colorado State University, Colorado Water Center

Chapter 3
Cameron Bracken, Bonneville Power Authority
Kevin Wheeler, Water Balance Consulting

Chapter 4
Andrew Newman, NCAR Research Applications Lab
Nancy Selover, Arizona State University, Arizona State Climate Office

Chapter 5
Kat Bormann, Jet Propulsion Laboratory, Caltech and NASA
David Clow, USGS Colorado Water Science Center
Mark Landers, USGS National Streamgage Network Coordinator

Chapter 6
Ben Livneh, CU Boulder, CIRES, WWA and Civil Engineering
Mark Raleigh, CU Boulder, CIRES, NSIDC
Peter Troch, University of Arizona

Chapter 7
Emily Becker, University of Miami, Cooperative Institute for Marine and Atmospheric Studies (CIMAS)
Kathy Pegion, George Mason University
Tom Hamill, NOAA ESRL Physical Sciences Division

Chapter 8
Guotao Cui, University of California, Merced
Kevin Werner, NOAA Northwest Fisheries Science Center

Chapter 9
Upmanu Lall, Columbia University, Columbia Water Center
David Tarboton, Utah State University, Utah Water Research Laboratory

Chapter 10
Toby Ault, Cornell University
Greg Pederson, USGS Northern Rocky Mountain Science Center

Chapter 11
David Pierce, Scripps Institution of Oceanography and California-Nevada Climate Applications Program (CNAP)
Julie Vano, Aspen Global Change Institute

Other contributors

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Genevieve Allan, Bureau of Reclamation, Lower Colorado Region
Sarah Baker, CU Boulder, CADSWES and Bureau of Reclamation
Dan Bunk, Bureau of Reclamation, Lower Colorado Region
Alan Butler, Bureau of Reclamation, Lower Colorado Region
Marty Hoerling, NOAA ESRL Physical Sciences Division
John Lhotak, NOAA NWS Colorado Basin River Forecast Center (CBRFC)
Scott McGettigan, Utah Division of Water Resources
Matt Miller, USGS Earth Systems Modeling Branch
Paul Miller, NOAA NWS CBRFC
Naoki Mizukami, NCAR RAL
Balaji Rajagopalan, CU Boulder, CIRES and Civil Engineering
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Colorado River Basin Climate and Hydrology

State of the Science

Executive Summary

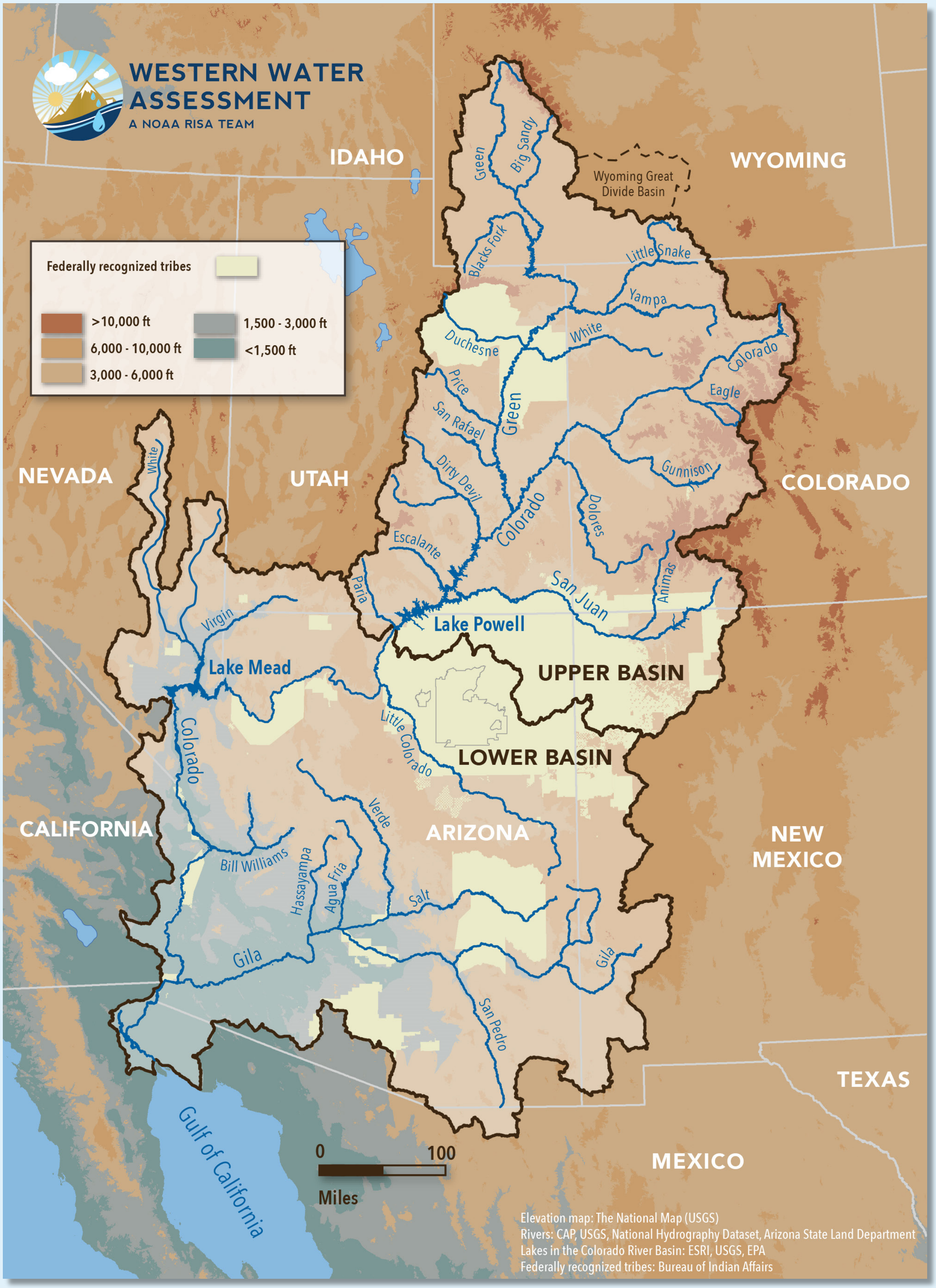
The Colorado River Basin currently faces unprecedented stresses. Persistent dry conditions since 2000, along with the increasing recognition that warming temperatures are impacting the hydrology of the basin, have led to great concerns about the long-term reliability of basin water supplies. With ever-higher stakes for water resource planning and decision making, an even greater emphasis is placed on the tools that support those activities, notably Reclamation's operations and planning models and similar models used at other agencies. The usefulness of these system models depends on many types of datasets and forecasts that serve as inputs to them, as well as the research and scientific understanding underpinning this complex chain of data and models. The development and refinement of the different links of the chain necessarily involves researchers, forecasters, and water managers.

New research efforts have advanced our understanding of the hydroclimate of the basin and how key hydroclimate processes, variability, and changes can be captured in data and models. This rapid expansion of the scientific knowledge base, and the increasing complexity of the data and models used to operationalize that knowledge, parallel the growing uncertainties about the future climate and hydrology. Accordingly, basin stakeholders have recognized the importance of reassessing the scientific and technical basis for management and planning.

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

Past scientific advances have led to improvements in the various links in the chain of data and models, and to more accurate and actionable information for decision making. The ongoing efforts documented in the report strongly suggest that this progress will continue. At the longer time scales, however, research reveals and affirms large uncertainties that are difficult to reduce given both natural variability and the imperfections in our understanding, observations, and models, and our inability to fully test our predictions.

Each chapter of the report focuses on one major link in the chain of data and models, covering a broad array of activities to better observe, model, forecast, and understand the climate and hydrology of the basin. Key points from each chapter are presented below, as well as a summary of the challenges identified in each chapter and the opportunities to address those challenges. Readers are encouraged to explore the full report for the context supporting these key points and challenges and opportunities.



The Colorado River Basin

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

Key points

- On average, about 170 million acre-feet (maf) of precipitation falls over the Colorado River Basin annually, but only about 10% (17 maf) becomes natural streamflow available for use.
- The Upper Basin contributes the vast majority, about 92%, of the total basin natural streamflow as measured at Imperial Dam.
- Elevation dramatically shapes the amount of precipitation and its relative contribution to runoff, so that 85% of annual runoff comes from the 15% of the basin's area that is located in the mountain headwaters.
- The position and activity of the mid-latitude storm track from October through May is the critical climatic driver of annual precipitation in the basin's headwaters.
- Snowmelt is the primary source of annual runoff from those mountain headwaters, as reflected in the prominent late-spring peak in the annual hydrograph.
- Year-to-year variability in runoff is high and is mainly driven by variability in precipitation; decadal and multi-decadal variability in precipitation and in runoff is also present but no consistent cycles have been identified.
- The predictability that does exist at shorter time scales (up to 1 year) comes mainly from the El Niño-Southern Oscillation (ENSO); the ENSO signal is generally weak in the Upper Basin but stronger in the Lower Basin.
- Predictability at decadal and longer time scales using longer-lived climate phenomena (e.g., Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation, etc.) has proven elusive.
- The period since 2000 has been unusually drought-prone, but even more severe and sustained droughts occurred before 1900.
- There has been a substantial warming trend over the past 40 years; the period since 2000 has been about 2°F warmer than the 20th-century average, and likely warmer than at any time in the past 2000 years.
- Decreases in spring snowpack and shifts to earlier runoff timing in many parts of the Upper Basin, as well as decreases in annual Colorado River flows at Lees Ferry, Arizona, have occurred in recent decades. These changes in hydrology can be linked, at least in part, to the warming trend.

Challenges and opportunities

Challenges

- There is still considerable uncertainty in the quantification of the relative roles of temperature, precipitation, antecedent soil moisture, dust-on-snow, and vegetation change in recent and ongoing variability and change in Upper Basin snowpack and streamflow.
- These factors have substantial spatial variability, but most studies have conducted analyses and presented findings only at the Upper Basin-wide scale (e.g., at Lees Ferry).

Opportunities

- Conduct analyses of Upper Basin hydrologic change that are spatially disaggregated at least to the eight major sub-basins (Upper Green, Yampa-White, etc.), or focus only on the most productive headwaters areas, or both.
- Pursue the various pathways to improve hydrologic modeling presented in Chapter 6.
- Conduct intercomparisons of hydrologic models and statistical methods for assessing the factors behind hydrologic changes.

Chapter 3. Primary Planning Tools

Key points

- Three monthly Reclamation models, developed in RiverWare™, support planning at three time scales: 1) 24-Month Study (24MS) for short-term planning (up to 24 months), 2) Mid-Term Probabilistic Operations Model (MTOM) for mid-term planning (up to 60 months), and the Colorado River Simulation System (CRSS) for long-term planning (multiple decades).
- The models use rules to incorporate operational policies set forth in Records of Decisions and other operational agreements, and some long-term studies also explore potential alternative policies.
- Hydrologic inputs to the short-term and mid-term models are either flows forecast by the NOAA Colorado Basin River Forecast Center (CBRFC) or statistical averages of observed flows.
- Hydrologic inputs to the long-term model may be based on historical hydrology, paleohydrology, climate change-informed hydrology, or hybrids.
- Measured Upper Basin water demands for the short-term and mid-term models are accounted for in the CBRFC's forecast; Lower Basin water demands are provided by Lower Basin water users and Mexico. Both Upper and Lower Basin demands for the long-term model are based on projections supplied by water users.
- Uncertainties, errors, and limitations arise from input data sources, assumptions about the future, and necessary simplifications of a complex water supply system.

Challenges and opportunities

Challenge

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

Opportunities

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

Challenge

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

Opportunities

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

Challenge

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

Opportunities

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

Chapter 4. Observations—Weather and Climate

Key points

- Weather and climate data are collected and interpolated for specific reasons, so not all data and datasets are suitable for all uses. Users should be cautious about "off-label" use of climate data and should thoroughly investigate the suitability of data before it is applied outside of its planned uses.
- Users of weather and climate datasets should be aware that the data reflect average or summary conditions over their spatial and temporal resolution and should not expect a gridded product to accurately reflect conditions at any particular point on the landscape at any given point in time. This is particularly true for high-relief landscapes like the Colorado River Basin.
- Most of the existing high-resolution gridded datasets share some base information or use similar processing, or both, so they are not strictly independent.
- There is not now, and likely never will be, perfect weather and climate data. Producers of climate information need to communicate, and users should be cognizant of, the strengths and weaknesses of the data they choose and how climate data choices influence their conclusions.
- In the Colorado River Basin, the highest elevations have the lowest weather station densities and likely the least precise and accurate weather information. This is especially problematic for water resource questions, because such a large fraction of the runoff is generated at high elevations.

Challenges and opportunities

Challenge

While commonly used gridded climate datasets show very similar variability and trends in precipitation and temperature for the basin, disagreements between the datasets are larger for the sparsely instrumented high-elevation areas in the Upper Basin—the areas that generate the vast majority of the basin's runoff.

Opportunities

- Use other types of measurements, such as streamflow and radar, to constrain the gridded estimates of temperature and precipitation, and add novel observation techniques (e.g., Airborne Snow Observatory) to bolster ongoing observations.

- Use numerical weather prediction models for spatiotemporal interpolation and validation of observation-based products.

Challenge

It is increasingly understood that the gridded climate datasets have inherent uncertainties and differ from each other, but how those uncertainties and differences manifest in the outputs of typical hydroclimate modeling and analysis tasks needs to be better explored and communicated to users.

Opportunities

- Conduct formal intercomparisons between gridded datasets in the context of specific applications and outputs (e.g., Alder and Hostetler 2019 on the use of different gridded climate datasets for statistical downscaling of GCM data).
- Application projects can consider including a testing phase in which multiple gridded datasets are tested on a limited portion of the project's domain or analyses.
- Both researchers and users can acknowledge that all data are imperfect, and move away from trying to identify a single "best" product toward greater consideration of the data characteristics that are, and are not, important for their questions and analyses.

Chapter 5. Observations—Hydrology

Key points

- Robust real-time observations and long-term records of snowpack, streamflow, soil moisture, and other hydrologic variables are key inputs to basin streamflow forecasting and system modeling.
- Point measurements of these variables are not dense enough to fully represent spatial variability across the basin, and not necessarily sited to optimally inform streamflow forecasts.
- For snowpack observations, the in situ SNOTEL network has limitations but remains essential to monitoring and skillful streamflow forecasting.
- Spatially distributed snowpack data from models and remote sensing are increasingly used to augment SNOTEL data, though most of these sources depend on SNOTEL data for calibration.
- Accurate and useful streamflow inputs depend on both the robustness of the gage network and the procedures used to adjust and naturalize gaged streamflows to account for human activity.
- Flow naturalization methods try to estimate what the streamflow at a gage would have been, or will be, without the impacts of upstream human activity; naturalization methods vary from agency to agency, depending on the time scale and application.
- Evaporation and evapotranspiration estimates are central to flow naturalization, thus as more types of observations become available, models used to calculate these variables are being refined in both physical process modeling and input data used.
- In situ measurements of soil moisture and evaporation-related variables are especially sparse, and spatially distributed data from models and remote sensing have a larger role to play in condition monitoring and streamflow forecasting.
- Realizing the full value of spatially distributed hydrologic data will ultimately require streamflow-forecasting and system-modeling frameworks that are explicitly designed to use those data as inputs.

Challenges and opportunities

Challenges: Snow

- Inadequate characterization of the snowpack is still a major source of error in streamflow forecasts, especially in years with anomalous patterns of snow distribution in space and time—a phenomenon which appears to be more frequent in a changing climate

- The in situ (point) snow course and SNOTEL network was designed for the statistical streamflow forecasting paradigm, which is no longer used by CBRFC.
- Many new spatially distributed SWE products are now available, but there have been few rigorous evaluations of these datasets, in part because it is difficult to validate spatial products with point measurements.
- The SNOTEL network will remain essential to any conceivable future snow monitoring system in the basin, especially with additional sensor capacity at SNOTEL sites, but the network has been inadequately supported in recent years by USDA.

Opportunities

- Building on recent smaller scale pilot efforts to conduct larger scale, systematic intercomparisons of SWE datasets and products for the basin, including SNOTEL, ASO, and SNODAS and other spatially distributed modeled products.
- Based on the results of such intercomparisons, pursuing "hybrid" approaches where multiple methods and datasets are combined in a way to best exploit their relative advantages.
- Continuing and stepping up the modernization and expansion of the SNOTEL network, with more and better sensors, more imagery, and better data communication—all of which would necessitate more resources for NRCS to support the network.

Challenges: Streamflow

- Streamflow observations that could contribute to more accurate naturalization calculations are not available at many key sites, especially diversion and return flow locations.
- Naturalizing the gage record requires adjustments that come with potential errors and uncertainties, many of which are impossible to address or resolve because of the dearth of early-period data and documentation.
- Fully characterizing the natural hydrology of the basin is problematic with the exclusion of the Gila River from consideration.
- A number of research activities use Reclamation's natural flow record for baseline or reference purposes. For example, synthetic streamflow generation relies on the natural flow record for parameter estimation or for nonparametric sampling, tree-ring reconstructions of paleostreamflows are calibrated against the natural flows at Lees Ferry, and hydrologic simulations from the Variable Infiltration Capacity

model that are used to project future streamflows were bias-corrected based on the natural flows at Lees Ferry and other gaging stations.

Opportunities

- Regarding gaging, the biggest gains in information going forward would be achieved by expanding the streamflow monitoring network to fill gaps in coverage. This includes gages at diversion sites and in locations to measure return flows or verify return flow and gain/loss calculations.
- Increasing the spatial resolution of Reclamation's models might be a useful avenue to pursue in order to simulate and analyze impacts from climate change on sub-basin hydrology.
- Major modifications to the natural flow record, to improve consumptive use estimates for example, have implications for both the calibrations and other applications listed above, and for the record extension back to 1906 because the extended records were based on statistical analyses of the natural flow record that was in place at the time of extension. As more recent natural flow data becomes available, there is an opportunity to revisit the characterizations, calibrations, bias-corrections, and record extension that were based on earlier versions of the natural flow record.

Challenges: Soil moisture and evaporation

- Compared with snowpack (which is variable over space and time), soil moisture is poorly monitored and understood, with frequent discrepancies between in situ measurements and modeled estimates.
- Real-time soil moisture data is collected from at least 6 different in situ networks, with differing observing protocols (depth, etc.).
- Reservoir evaporation estimates as used in basin system modeling have been based on decades-old data that does not reflect current climate conditions.
- Estimates of evapotranspiration and crop water use have been constrained by physically incomplete methods and input data that are not spatially representative.

Opportunities

- Support and expand ongoing efforts to comprehensively collate in situ soil moisture measurements and merge these observations with spatially distributed modeled estimates (e.g., National Soil Moisture Network).
- New satellite sensors and products (e.g., SMAP) that provide spatially comprehensive and consistent soil moisture estimates can likewise be compared and blended with other types of soil moisture data.

- When applicable, conduct testing of new soil moisture products to determine if they add value to the CBRFC forecast process.
- Ongoing efforts will provide updated reservoir evaporation estimates for Lakes Mead and Powell; those efforts could be expanded to other large reservoirs in the basin.
- Expand the in situ monitoring of evaporation/ET/PET with enhanced weather stations that capture all four variables needed for fully physical estimates (e.g. the Penman-Monteith method), and new flux towers needed for the Eddy Covariance method.
- Better in situ data will also help in calibrating/validating remote sensing-based spatial estimates of ET and crop water use; use of these spatial estimates in the basin has been increasing, though it has been limited by user confidence in the data.

Chapter 6. Hydrologic Models

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.

Challenges and opportunities

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. 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), 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.

Chapter 7. Weather and Climate Forecasting

Key points

- Uncertainty about upcoming weather and climate conditions translates into a major source of uncertainty in seasonal streamflow forecasts.
- Weather forecasts out to 10 days have relatively high skill and are progressively improving; they are incorporated into the CBRFC's operational streamflow forecasts.
- Sub-seasonal (2 weeks to 12 weeks) and seasonal (3 months to 1 year+) climate forecasts have much lower skill, especially in the Upper Basin, and they are not incorporated in the CBRFC streamflow forecasts.
- A major research effort has ramped up in the last decade to advance sub-seasonal and seasonal forecasting.
- Sub-seasonal and seasonal forecasts for temperature are generally more skillful than forecasts for precipitation, and skill for both is generally higher for the Lower Basin than for the Upper Basin.
- For precipitation, the Climate Prediction Center's seasonal forecast skill in both basins has been positive for winter and spring, suggesting users should focus their forecast use on those seasons.
- There are other opportunities to better utilize the skill that does exist in sub-seasonal and seasonal climate forecasts, such as using them to "nudge" the streamflow forecast ensemble during post-processing.

Challenges and opportunities

Challenge

Limitations in our understanding of the connections between atmospheric and oceanic circulation patterns and processes, and Colorado River Basin precipitation variability in space and time, constrain the skill of climate forecast models in forecasting conditions for the basin.

Opportunities

- Support further research into these climate system dynamics to identify key patterns and variables.
- Support further research into better representing those key patterns and variables in dynamical climate forecast models and statistical forecast tools.

Challenge

The CBRFC and other streamflow forecasting units may not be able to capitalize on the skill that does exist in sub-seasonal and seasonal climate forecasts for the basin.

Opportunities

- Support ongoing CBRFC efforts to pilot the inclusion of sub-seasonal and seasonal forecasts in their forecast system.
- Support further research into post-processing of CBRFC forecasts to generate climate-forecast-informed, use-specific streamflow forecasts.

Challenge

The limited skill and probabilistic nature of climate forecasts may not mesh well with decision frameworks so water managers are unable to extract value from the forecast information.

Opportunities

- Continue to support engagement between water managers and CPC and other climate forecasters to facilitate shared understanding of decision needs and forecast capabilities.
- Study decision making by users and sectors that make better use of climate forecasts (e.g., crop futures traders), to assess transferability of tools and practices.
- Develop decision support tools that bridge climate forecasts to the water resource decision space.

Challenge

The skill of climate forecasts is highly variable over both space and time, complicating the consistent use of forecasts.

Opportunities

- Selectively consult forecasts during those seasons when they have shown the most skill for the basin.
- Support research to identify “forecasts of opportunity” specific to the basin, i.e., conditions of the ocean, atmosphere, and land surface during which forecasts are more likely to have skill and impact.

Chapter 8. Streamflow Forecasting

Key points

- Streamflow forecasts from the CBRFC are widely used by water managers in the basin and are critical inputs for Reclamation's operational models, including seasonal forecasts for use in 24MS and MTOM.
- Streamflow predictability at seasonal timescales in the Colorado River Basin arises primarily from the initial watershed moisture conditions, i.e., snowpack and soil moisture.
- While using different methods, the CBRFC and NRCS operational forecasts both effectively capitalize on this predictability, with relatively high skill for forecasts issued in late winter and spring for the coming runoff season.
- To improve streamflow forecasts within the current frameworks there are two main pathways: 1) improve estimates of initial watershed moisture conditions, and 2) improve basin-scale weather and climate forecasts and how they are used in streamflow forecasts.
- Improvements in quantifying watershed conditions can come through better meteorological analyses, more in situ observations of snowpack and soil moisture, increased use of remotely sensed observations, advances in calibration strategies, and advances in data assimilation techniques.
- Improvements in sub-seasonal and seasonal climate forecasts are being actively pursued by national modeling centers and the broader research community; targeted post-processing of climate forecasts can better leverage their current skill to inform seasonal streamflow forecasts.
- Skill in streamflow forecasts for year 2 and beyond is entirely dependent on skill in decadal climate forecasts, which exists to some degree for temperature but not for precipitation.
- Alternative forecast frameworks in which tasks are fully automated permit the use of a greater range of advanced methods and data. These frameworks have not yet been shown, however, to outperform the current operational forecasts.
- Many potential forecast improvement elements have been demonstrated in a research context; systematic testing to benchmark and combine multiple elements could add up to significant overall improvements in operational forecasts.

Challenges and opportunities

Challenge

The modeling advances over the last three decades and their demonstration in forecasting contexts have not altered the reliance of RFC operational practices on the legacy models. There is a clear scientific rationale for enhancing the physics of the legacy models in many forecast cases, yet implementing modeling advances faces major hurdles for operational flow prediction in both the current in-the-loop forecast paradigm and the over-the-loop workflow.

Opportunities

- Effective approaches for regional parameter estimation (calibration) in more complex watershed process models to enable model streamflow simulations on a par with the performance of current legacy models.
- Effective approaches for automated hydrologic data assimilation, to replace the many manual adjustments made by expert forecasters and enable skillful over-the-loop systems.
- Automated interoperability of water management decisions and river basin modeling systems, to replace the manual incorporation of management effects like releases and diversions.

Challenge

There is little question that more extensive monitoring of watershed conditions, either by direct or remote measurements, would benefit hydrologic forecasting. The benefits can arise in two ways: 1) improving real-time analyses that provide the initial conditions for forecasts, which matter most when those conditions provide most of the forecast signal, such as in late spring; and 2) improving model implementation by helping constrain model parameters and guide structural implementation of those parameters.

Opportunities

- Expansion of real time measurements of streamflow, snow water equivalent (SWE), soil moisture, and ET.
- Methodological research into how observations that are sparse or coarse (e.g., soil moisture) or collected as snapshots (e.g., ASO SWE) may be incorporated into a forecast workflow.
- Development of both real-time and multi-year (retrospective) records that provide a foundation for research and methodological verification.

Challenge

To open the door for adoption of more complex models, multi-faceted ensemble approaches, leveraging supercomputing, and other advancements in streamflow forecasting, the research and operational communities must develop effective automated hydrologic data assimilation methods.

Opportunity

- Experimentation and refinement of automated hydrologic data assimilation, particularly to enable over-the-loop prediction.

Challenge

It is clear that improved sub-seasonal (S2S) and seasonal climate predictions would have substantial benefit for mid-range hydrologic predictions, with a particular need for cool-season precipitation forecasts in the runoff-generating regions of the western U.S. Yet, S2S climate prediction has also long been a major scientific challenge, requiring large scale investments by the Earth system research community in improved global-scale observations, climate modeling, climate model data assimilation systems, and predictability studies.

Opportunity

- Invest in analysis and development of watershed-scale climate forecasts via both empirical and dynamical methods and sources as operational climate forecasting capabilities slowly evolve.

Challenge

The lack of a hydrologic forecasting testbed is a critical institutional gap. Support is needed to transition new research to operations for both the National Water Center and for the RFCs, and build the case for the viability of over-the-loop approaches.

Opportunity

- A testbed would support experimentation and systematic development of real-time forecast approaches, including new models, data assimilation techniques, post-processing approaches, model calibration techniques, climate and weather downscaling methods, verification and communication related to forecasts, and decision making.

Chapter 9. Historical Hydrology

Key points

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

Challenges and opportunities

Challenge

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

Opportunity

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

Challenge

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

Opportunities

- Explore performing diagnostics on the parameters used in parametric stochastic streamflow studies in the Colorado River Basin to assess the dependencies between and among parameters and to assess the complexities involved in incorporating non-stationarity into them.
- Techniques for generating long-term streamflow sequences that blend historical observed hydrology with paleohydrology or climate change-informed hydrology (or both) offer substantial promise. The paleo record offers extremes, durations, and frequencies not seen in the observed record, and the climate change-informed hydrologies offer potentially altered climate patterns and regional shifts that are absent or undetectable from the observed and paleo records.
- A potentially useful effort might be to review approaches to other variables, and even other disciplines, for techniques that could be translated into streamflow synthesis techniques.

Chapter 10. Paleohydrology

Key points

- Tree-ring reconstructions of Colorado River streamflow extend the observed natural flow record up to 1200 years into the past and document a broader range of hydrologic variability and extremes than are contained in the observed records.
- Most critically, several paleodroughts prior to 1900 were more severe and sustained than the worst-case droughts since 1900.
- These "megadroughts" could recur in the future due to natural climate variability alone, but their recurrence risk is much increased by anthropogenic warming.
- The century-scale mean and variability of Colorado River Basin hydroclimate has not been stationary over time.
- The early 20th century high-flow years (1905–1930) may have been the wettest multi-decadal period in 500–1000 years.
- Methodological choices in the handling of the tree-ring data can influence the reconstructed flow values and metrics, such as the duration of droughts.
- Planning hydrologies derived from tree-ring paleohydrology can provide plausible stress tests that are more extreme than the observed hydrology, and have been used for that purpose in several recent planning studies in the basin.

Challenges and opportunities

Challenge

At present, only seven tree-ring site chronologies in the Upper Basin extend beyond 2005, so current streamflow reconstructions do not have the benefit of full calibration against the early 21st century dry period. Additionally, Reclamation's ongoing revisions of natural flow estimates may, cumulatively, substantially revise the target hydrology for tree-ring flow reconstructions.

Opportunities

- Develop new or updated tree-ring site chronologies that the can be included in the calibration of any forthcoming streamflow reconstructions.
- Consider recalibration of, as well as assessment of the sensitivity of, the tree-ring flow reconstructions to the revised natural flows.

- Generate new, targeted reconstructions for the key water supply regions of the Upper Basin like the ongoing project funded by the USGS Southwest Climate Adaptation Science Center, in collaboration with basin water managers.

Challenge

Key to applications of paleohydrology to future climate scenarios is understanding how modes of natural variability itself will change over the coming decades. It is unclear which methods of blending paleohydrology data and climate projections have the most robust physical foundation, and more work is needed to examine the issue of persistence in streamflow reconstructions and to determine its source.

Opportunity

- Develop plausible scenarios and characteristics of future basin drought over the next several decades through integration of paleohydrology data and climate projections. Some of this work is underway, as described above.

Challenge

Existing tree-ring reconstructions of annual and growing-season temperature for the basin are not nearly as skillful as reconstructions of precipitation and streamflow, limiting our ability to tease apart the drivers of past low-flow periods and place the recent warming trend in context.

Opportunity

- Renew efforts to develop a robust reconstruction of past basin temperatures, building on current investigations using bristlecone pine, plus updating and re-measuring other collections of trees that are limited in growth by temperature.

Chapter 11. Climate Change-Informed Hydrology

Key points

- Climate change-informed hydrology is increasingly used in basin planning studies to complement other long-range hydrologic information.
- Most approaches to developing this information begin with global climate models (GCMs) driven by one of several emissions scenarios; the approaches incorporate multiple processing steps, with corresponding methodological choices that each have implications for the final output and its uncertainty.
- GCMs are the best tools we have for exploring and quantifying physically plausible future climate changes at global to sub-continental scales. They have deficiencies in representing some key climate system features relevant to basin-scale climate, as well as reproducing historical basin-scale climate patterns themselves.
- Downscaling methods make GCM output more usable for finer-scale hydrologic modeling, such as projections of future streamflows. Downscaled projections are not necessarily more accurate than the underlying GCM output in depicting future climate change.
- Further warming is projected by all GCMs to continue in the basin as a consequence of continuing greenhouse gas emissions; basin temperatures are projected to rise by 2.5°F–6.5°F by mid-century relative to the late 20th century average.
- The direction of future precipitation change for the basin is much less certain than temperature change. The GCMs show some overall tendency toward increasing annual precipitation in the northern parts of the Upper Basin, and toward decreasing precipitation from the San Juan Basin south through the Lower Basin.
- The projected trends in precipitation are relatively small compared to the high year-to-year natural, or internal, variability in precipitation. Most GCMs project increased precipitation variability in the future.
- Mainly due to the pervasive effects of warming temperatures on the water cycle, nearly all of the many datasets of climate change-informed hydrology and related studies show a strong tendency toward lower annual runoff volumes in the Upper Basin and the Lower Basin, as well as reduced spring snowpack and earlier runoff.
- The overall spread of potential future hydroclimatic changes for the basin, as depicted across the GCM-driven projections, has not been reduced over the past decade and may not be appreciably reduced by

forthcoming data and methods, not least because much of the spread is due to unpredictable natural climate variability.

Challenges and opportunities

Challenge

GCM disagreements in changes of key climate variables: 1) GCMs do not agree on the magnitude of warming to expect globally, or in the basin, for a given emissions scenario-timeframe combination; 2) GCMs do not agree on the direction and magnitude of annual precipitation change for the basin. Based on past history, further improvements in GCMs (e.g., better resolution of CMIP6 GCMs) will likely only slowly reduce these disagreements.

Opportunities

- Pursue additional guidance beyond the GCM ensemble regarding changes in these uncertain variables, e.g., recent observed trends, climate theory, and expert opinion (e.g., surveys of researchers).
- Identify specific hydroclimate conditions, events, and sequences that lead to vulnerability; there may be greater consensus among the GCMs regarding these than in the changes in annual or seasonal average precipitation, for example.

Challenge

Due to GCM uncertainty and other factors, the range of projected future outcomes for basin hydrology (e.g., change in annual runoff volume at Lees Ferry) from GCM-based ensembles is very broad, and most planning decisions cannot address the full range of potential future conditions without incurring regrets from under- or over-preparation.

Opportunities

- Methods are available (e.g., scenario development, hydrologic storylines) to at least reduce the number of traces from the ensemble, improving their tractability for planning, and potentially identifying more physically plausible and likely outcomes.
- Alternative planning paradigms may be more appropriate for decision making under deep uncertainty. In planning, emphasize those outcomes associated with greater vulnerability and impacts, i.e., drier projections.

Challenge

GCM resolution, while improving, is still coarser than that required for realistic modeling of basin hydrology and system modeling, requiring the application of downscaling methods.

Opportunity

- The HighResMIP experiment within CMIP6 will soon make available an ensemble of GCM projections at 25–50 km resolution. This is still coarser than the resolution optimal for hydrologic modeling but will provide a useful test of what added value can be expected from high-resolution GCMs.

Challenge

Statistically downscaled projection datasets, which dominate applications of regional climate data in water supply assessments, are perfectly adequate as sequences to input in hydrology models, but they add little to our physical understanding of future changes beyond what the GCMs can tell us. The very high resolution of these datasets (1–12 km) can also mislead users as to their accuracy and added value.

Opportunity

- For water supply assessments, look to dynamically downscaled or hybrid methods and datasets (e.g., NA-CORDEX, ICAR, En-GARD) for more physically oriented guidance that can provide context for statistically downscaled datasets, or replace them.

Challenge

The sources of uncertainty and differences in climate change-informed hydrology for the basin have been identified and explored to varying degrees, but not fully examined, including the underlying methodological choices. Thus, data users have incomplete information about uncertainty, and may not be aware of the subjective choices underlying particular results of hydrologic assessments.

Opportunities

- Support comprehensive evaluations of the differences stemming from downscaling methods, bias-correction methods, and hydrologic models.
- Provide visualization tools of future climate and hydrology that are not limited to a single dataset and allow the users to toggle between datasets to clearly see commonalities and differences.

Challenge

Any given ensemble of climate change-informed hydrology (e.g., CMIP5 BCSD) is a complex dataset that is challenging to obtain, analyze, and interpret; the increasing proliferation of similar datasets and their respective underlying methodological approaches can be bewildering to even sophisticated users.

Opportunities

- For both researchers and practitioners, support efforts to provide guidance on the appropriate use of existing datasets, e.g., Vano et al. (2018), and WUCA training workshops.
- Develop and disseminate new methods and datasets only when there is a compelling use case and clear added value over existing datasets.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