PROCEEDINGS OF THE

2017 Colorado River Hydrology Research Symposium

May 22-23, 2017
Springs Preserve, Las Vegas, Nevada

FOREWORD

The Southern Nevada Water Authority is pleased to recognize the individuals and agencies that supported the Colorado River Hydrology Research Symposium, hosted in Las Vegas, Nevada, on May 22 and 23, 2017. The Planning Committee invested significant time and thoughtful consideration into program development, working to create a forum for the meaningful exchange of ideas and information between water resource managers and the hydrologic research community. Together, through formal presentations and facilitated dialogue, symposium presenters and audience participants offered their unique perspectives, explored ways to address information needs, and discussed potential opportunities to enhance hydrologic planning tools used to support basinwide decision-making efforts.

Colorado River Hydrology Research Symposium Planning Committee

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The Southern Nevada Water Authority also is pleased to recognize the Springs Preserve for sponsoring the symposium, as well as the Springs Preserve Youth Advisory Council for assisting with logistical arrangements.

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ACRONYMS AND ABBREVIATIONS

24-MS	24-Month Study
ASO	Airborne Snow Observatory
CBRFC	Colorado Basin River Forecast Center
CRLE	Complementary Relationship Lake Evaporation
CRSS	Colorado River Simulation System
DRI	Desert Research Institute
ENSO	El Niño/Southern Oscillation
ESP	Ensemble Streamflow Prediction
GCM	General Circulation Model
GEFS	Global Ensemble Forecast System
JPL	Jet Propulsion Laboratory
MODIS	Moderate Resolution Imaging Spectroradiometer
MTOM	Mid-Term Operations Model
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
PET	potential evapotranspiration
Reclamation	U.S. Bureau of Reclamation
RTI	RTI International
SWE	snow water equivalent

SYMPOSIUM OVERVIEW

The Colorado River Hydrology Research Symposium was attended by more than 100 water resource management, technical and research professionals conducting work in (or applicable to) the Colorado River Basin. These participants represented federal agencies, state water agencies, regional water purveyors, water resource managers, and university-affiliated researchers. Through formal presentations and facilitated discussions, participants worked to gain a better understanding of new hydrologic research initiatives; investigate innovative ways that research could potentially be used to support climate change adaptation and response efforts within the Colorado River Basin; and explore how research could be applied to enhance existing predictive tools. Research professionals provided insight on potential opportunities to improve model inputs and results, while resource management professionals identified practical information needs and possible opportunities to enhance model performance. Symposium participations did not engage in policy discussions, but focused their time and attention on ways to enhance the data, science and models used to support policy and decision-making processes.

The symposium consisted of nine panel sessions, including several "Success Stories," in which research professionals demonstrated how they have successfully transferred project research into applied practice. Each session focused on a major topic or theme and included several presenters. Sessions on the first day of the symposium explored short-term seasonal to multi-year forecasting, while sessions on the second day focused on developments in long-term projections.

Each program day began with a detailed explanation of the inputs, outputs and uses of major U.S. Bureau of Reclamation (Reclamation) models that are used to develop forecasts and/or projections. These models include the 24-Month Study (24-MS), the Mid-Term Operations Model (MTOM) and the Colorado River Simulation System (CRSS) model. Symposium participants recognized the importance of these tools in basin-wide decision-making processes, as well as the far-reaching impacts those decisions can have on regional water users and resource managers.

Short-term forecasting was a prominent theme in first-day discussions. Short-term forecasts on a seasonal to five-year timeframe from the 24-MS to MTOM models provide estimates of inflows, reservoir operations, and outflows that inform operating criteria across the Colorado River Basin. Symposium participants recognized the importance of accurate streamflow forecasts to model results and offered suggestions for improving short-term forecasts, including more accurate snow and improved evapotranspiration (ET) data.

Participants discussed recent developments in long-term projections during the second day, with emphasis on climate change. This included a review of the CRSS model, which serves as the common long-term planning and policy model for the Colorado River Basin. Several presenters provided information on how future inflow projections are being improved, a key model input with the largest effect on CRSS results. Other discussions included the impacts of climate change on Colorado River Basin hydrology, including increased temperatures, increased frequency and severity of droughts, and changes related to the timing of seasonal snowmelt. Likewise, participants discussed changes in temperature, which are expected to increase reservoir evaporation and agriculture ET rates. These factors can impact water supply and water demand in the Colorado River Basin.

Discussions also addressed the gap between short-term and long-term forecasting, particularly with predictions in the five-year to decadal range. The gap arises due to model reliance on observed current conditions (short-term forecast) and use of long periods of data to ascertain trends (long-term projections). Participants heard about work being done by the National Center for Atmospheric Research (NCAR) and Reclamation to address the gap in prediction, and to provide actionable information for water managers.

Decision-making under uncertainty was another major discussion topic during the symposium. While participants agreed that modeling tools have become increasingly more sophisticated over time, they acknowledged that they are not perfect as evidenced by the unexpected “Miracle May” and the wet 2015/2016 year. While steering clear of specific policy discussions, attendees shared their knowledge about how uncertainty is factored into water planning models, and how that uncertainty is being addressed. Participants pointed to Colorado River conditions as an example of decision-making under uncertainty. After teetering for many years on the edge of shortage, they emphasized worst-case scenario planning and shared their perspectives on appropriate science messaging to the public. Participants came to general agreement that additional work is needed to effectively communicate uncertainty to the public and stakeholders when sharing forecast information.

The following pages include a brief summary of symposium sessions and speaker presentations, as well as a summary of the dialogue that followed in each session’s general discussion. Copies of speaker presentations are provided in Appendix 1 and presentation abstracts are provided in Appendix 2.

Session Summaries

Session 1: Data and Models Used in Seasonal Streamflow Forecasts

KEY THEMES:

- 24-MS and MTOM models are the primary tools used in mid-term streamflow forecasts in the Colorado River Basin
- Specific improvements to the MTOM model have been identified

PRESENTATIONS:

Overview of Data and Models used to Develop 24-MS and MTOM Inputs

John Lhotak, Development and Operations Hydrologist

National Oceanic and Atmospheric Administration, Colorado Basin River Forecast Center

Mr. Lhotak described the basic components of seasonal streamflow forecast modeling. He explained that MTOM combines Colorado Basin River Forecast Center (CBRFC) streamflow forecasts with initial reservoir conditions and operational rules to produce a probabilistic forecast of future reservoir conditions. He explained that CBRFC develops future streamflow forecasts using the Ensemble Streamflow Forecasts (ESF) with the Ensemble Streamflow Prediction (ESP) function. The ESP technique uses water-year annual patterns of precipitation and temperature as separate future scenarios to be analyzed in a probabilistic fashion. The most common measures used to examine output are the 50 percent exceedance value taken as the most probable forecast, and the 10 percent and 90 percent scenarios.

Mr. Lhotak identified several future seasonal streamflow forecast research needs and suggested that forecasts could be improved by using current exports in the model and an estimation of in-basin irrigation within CBRFC models. He added that further evaluation of the model's accuracy compared to other seasonal forecasts is necessary, especially regarding model "skill." Mr. Lhotak indicated that work on transferring the model from a point data to gridded data basis is on-going. This will allow for the eventual development of an energy balance model in MTOM.

Overview of the 24-MS and MTOM

Shana Tighi, Hydrologist

U.S. Bureau of Reclamation

Ms. Tighi described Reclamation's mid-term operations and planning models, which include the 24-MS and MTOM. She said that the 24-MS is a deterministic operational model that uses a single hydrologic trace and manually input operations to determine operations for Colorado River reservoirs. The model also produces streamflow projections over a 1- to 2-year time horizon. Conversely, MTOM is a risk-based operational planning and analysis tool that uses rule-driven operations and probabilistic analysis to predict streamflow on a 1- to 5-year time horizon. MTOM was first released in June 2015 and was updated in January 2016 with minor adjustments. She indicated that results under normal hydrological conditions demonstrate the importance of initial conditions in the model, and said that an accurate inflow forecast improves overall forecast.

Ms. Tighi identified several areas for improvement of the models, both in terms of forecasting skill and modeling skill. She suggested that model forecasts could be improved in the 2- to 5-year horizon as model accuracy declines after the first year. She added that lower basin flows are largely driven by rainstorm events and that improving hydrology forecasting in the lower basin could be an area for improvement. More broadly, opportunities to improve these models lie in model inputs such as inflows, demands, and operating policies.

A New Framework to Evaluate the Skill of Different Hydrologic Forecasts Used in the 24-MS and MTOM

Sarah Baker, Hydrologic Engineer

U.S. Bureau of Reclamation

Ms. Baker presented information on a testbed that Reclamation developed to test MTOM streamflow forecast skill and operational projections to experimental forecasts. The testbed was formulated in RiverSMART to initialize at the beginning of each month for 1981-2016. The testbed simulates two years of streamflow, with a total of 420 simulations per forecast ensemble. Analysis of forecasts was split into two categories: hydrology metrics and operational projection metrics. Hydrology analysis examined annual Lake Powell unregulated inflow, which was selected because it is an aggregate of all upper basin streamflows. Ms. Baker explained that operational projections analysis focused on Lake Powell and Lake Mead's end-of-calendar-year pool elevations. She added that statistics computed in the testbed to analyze model skill included continuous rank probability skill score and root mean square error.

Ms. Baker reported the preliminary results of MTOM ESP. These indicate that the skill of the model in simulating annual Lake Powell inflow is about equal to the observed record at a 24-month outlook. ESP exhibits second year streamflow forecast skill better than the observed record starting in the fall of the second year (a 15-month lead) and has further increased skill by April (a 9-month lead). The ESP operational projections from MTOM indicate that the root mean square error of ESP decreases significantly by June of the first year of simulation. Ms. Baker indicated that evaluating experimental second-year streamflow forecasting methods and subsequently modeled operations in the testbed is a future research objective to be completed. She added that Reclamation also plans to extend these testbed simulations to 3- to 5-year projections.

GENERAL DISCUSSION:

Discussion for this session was brief and most questions pertained to specific aspects of the 24-MS or MTOM models. One symposium attendee revisited Mr. Lhotak's statement that better ET data is needed in the models, and asked about what is being used. Mr. Lhotak replied that the monthly values of ET are currently developed through calibration and best estimates, but offered that the next step in ET data is the development of a gridded dataset that is similar to the Parameter-Elevation Regressions on Independent Slopes Model. Similarly, he offered that the National Oceanic and Atmospheric Administration (NOAA) is looking to develop an 800-meter distributed temperature and precipitation input data for the streamflow forecast model to replace the current lump inputs. Ms. Tighi was asked about a forecast error in June in the MTOM model. She replied that this was more of an issue in the upper basin, and that forecasting improvement generally happens after operating decisions are made, typically following the official August 15-month forecast.

Session 1A: Success Story: Research to Applied Science

KEY THEMES:

- Modeling tools need to be presented in a form that policy makers can use and easily translate into decisions
- Collaboration between tool users and developers is key; customization of modeling tools for specific clients often leads to overall improvements to the models

PRESENTATIONS:

How the NASA JPL/CBRFC Collaboration Successfully Transferred Research to Applied Practice

Dr. Kat Bormann, Project Scientist

NASA Jet Propulsion Laboratory, California Institute of Technology

Dr. Bormann detailed the results of a National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) and CBRFC partnership that aimed to address questions related to snow and snowmelt, which are fundamental for operational forecasts. The presentation covered the basics of snowmelt, including the importance of short-wave radiation and the large role albedo plays in melt rates. Dr. Bormann indicated that dust has a large effect on snowmelt through albedo, which explains most of the behavior of the rising limb of the runoff hydrograph. This parameter has traditionally been difficult to predict, but has a large effect on seasonal forecasts. She added that melt rate is more correlated with snow dust and short-wave radiation than temperature in basins with snowpack.

Dr. Bormann noted that JPL aimed to capture snowmelt processes with observations in two distinct Moderate Resolution Imaging Spectroradiometer (MODIS) products: MODIS Snow Cover and Grain Size and MODIS Dust Radiative Forcing in Snow (MODDRFS). She explained that MODIS Snow Cover and Grain Size uses global scale observations at a 500-meter resolution to estimate fractional snow cover and grain size, while MODDRFS examines additional energy that is absorbed in snow cover due to dust. To integrate these observations into operational practice, snow accumulation and coverage observation data was imported to the SNOW-17 prediction model to estimate snow water equivalent (SWE). Operators at CBRFC also made manual melt factor adjustments in the model using observed dust radiative forcing data. Dr. Bormann noted that CBRFC is using daily distributed remote sensing products produced at JPL for near real-time operations. She attributed the success of these products, in part, to a feedback loop between clients and JPL, as well as continuous product enhancements made to address the clients' needs.

From Research to Application: Examples on the Colorado, Rio Grande, and Columbia Rivers

Dr. Edie Zagona, Research Professor

Department of Civil Engineering, University of Colorado Boulder

Director, Center for Advanced Decision Support for Water and Environmental Systems

Dr. Zagona described software applications developed by the Center for Advanced Decision Support for Water and Environmental Systems team at the University of Colorado Boulder to model river and reservoir behavior in the Colorado River Basin and other basins, focusing on the process of collaboration with basin experts to develop software to meet agency needs. She noted that the CRSS model, originally developed in the 1970s, was one of the most important developments in applied science in the Colorado River Basin. However, model shortcomings included procedural code, hardcoded policy, and the inability to distribute the model outside of Reclamation. She offered that a more dynamic and generalized program was needed for transparency, flexibility of operating policies, maintainability, and participation by stakeholders. Reclamation, together with other agencies, funded the new software, RiverWare, to be developed using state-of-art and innovative modeling concepts. It produced a tool that could be used to model a wide variety of types of basins, including the Colorado River Basin. Reclamation and the stakeholders re-created the CRSS model in the new RiverWare; the new software design was in large part driven by the Colorado River Basin modeling needs. She explained that other tools such as the RiverWare Study Manager and Research Tool (RiverSMART), a plugin based application that includes both RiverWare for river system modeling, and the Graphical Policy Analysis Tool (GPAT) for evaluating probabilistic of different proposed operating policies, were similarly driven by Colorado River Basin modeling needs and research and development of new modeling technologies.

Dr. Zagona indicated that these software applications have been used by numerous agencies for planning studies and real-time operations, resulting in improvements to functionality. For example, the Tennessee Valley Authority uses an innovative optimization formulation in RiverWare to schedule hydropower plant operations on an hourly basis. Likewise, Bonneville Power Administration uses RiverWare for both short-term planning and real-time operations to manage the Columbia River projects. Dr. Zagona also discussed the research and development of new modeling approaches for surface water and groundwater interactions driven by the needs of the Upper Rio Grande, allowing the managing agencies to more accurately operate the projects to meet flow quantity and salinity targets for water supply, environmental and interstate compact compliance.

Cloud Computing of Satellite and Gridded Climate Data: from Archives to Answers

Dr. Daniel McEvoy, Assistant Research Professor of Climatology

Desert Research Institute, Division of Atmospheric Sciences

Dr. McEvoy discussed methods used to translate large datasets into decision-making tools. While there is a bounty of easily accessible earth observations and environmental data, he offered that the community is lacking the tools to quickly process and visualize this data for decision-making. He noted that Google Earth Engine Cloud Computing has changed the paradigm of how satellite imagery and gridded weather data are processed and analyzed. This program allows for parallel processing of large archives of gridded data in the cloud. Although this technology has been extremely useful for the science community, Dr. McEvoy indicated that it still requires python or java programming knowledge to extract results.

Dr. McEvoy explained that the Desert Research Institute (DRI) has been working towards the goal of linking the Google Earth Engine to a web-based application called ClimateEngine.org that will put this information into the hands of policy makers. ClimateEngine.org allows for easy processing of drought and ecosystem metrics for anyone with a web connection. Crucially, it enables easy production of spatial maps using user selection of different dataset products, variables, and study areas. He noted that this tool has been applied to Lake Mead water quality monitoring, where a custom Climate Engine web page was developed for the National Park Service. He added that other applications include crop failure monitoring in Africa, crop/pumping/vegetation inventories, and water resource and ecosystem monitoring.

GENERAL DISCUSSION:

Symposium attendees discussed these collaborations, as well as the specific attributes that made them successful. Dr. Bormann offered that it was helpful to have someone on the ground who knew the tools well. She acknowledged that this approach is unrealistic in every situation and suggested that tools must be easy enough to use to make operational decisions on short notice. Participants also recognized challenges in these projects, including synthesizing massive amounts of data into easily-digestible formats using already existing tools, as well as resistance to change by software users. Dr. McEvoy offered another hurdle, which includes transferring knowledge about what the data means in application to users.

One participant posed a question regarding the level of responsibility product developers have in providing information to users about data quality and uses. Presenters agreed developers have a responsibility to their users, but that detailed documentation for each tool does not presently exist. Presenters emphasized that interaction with users is a key component in this process. Dr. McEvoy added that DRI currently takes requests for new datasets and changes the products based on user feedback to better suit their needs.

SESSION 2: IMPROVING SNOW DATA & MODELING

KEY THEMES:

- Advancements in remote sensing methods have allowed for accurate estimates of SWE, snow depth, and snow albedo
- Forecasts of seasonal streamflow runoff timing can be vastly improved by incorporating new data

PRESENTATIONS:

USING HIGH-RESOLUTION AIRBORNE SNOW OBSERVATORY PROGRAM DATA

DR. KAT BORMANN, PROJECT SCIENTIST

NASA JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY

Dr. Bormann discussed work done by the NASA JPL Airborne Snow Observatory (ASO) to use remote sensing for more accurate estimates of SWE in mountain ranges: this work was motivated by the identification of a spatial and temporal resolution void in currently available remote sensing data. Dr. Bormann offered that SWE and snow albedo are key to determining the magnitude and timing of snowmelt runoff, often the most important factor in water resources planning for the Colorado River Basin. Further, that snow depth variability is the most important variable defining SWE. She explained that ASO used infrared and Light Detection and Ranging instrumentation on individual flights over snow-covered areas to measure snow depth and snow albedo at 3-meter resolution. Observations were then used to produce SWE data at 50-meter resolution for use by water managers.

Dr. Bormann noted JPL can give basin-wide summaries of covered area, volume of snowpack water, mean snowline elevation, volume at each elevation band, and other crucial information. The product can be integrated into models through integration with Google Earth to use SWE spatial distribution data. She also mentioned the possibility of an ASO-like mission in space to map snow depth globally.

ASSIMILATION OF MULTIPLE DATA SETS TO IMPROVE SWE ESTIMATES: SNOWEX

DR. JEFFERY DEEMS, RESEARCH SCIENTIST

CO-OPERATIVE INSTITUTE FOR RESEARCH IN ENVIRONMENTAL SCIENCES /NOAA WESTERN WATER ASSESSMENT

NATIONAL SNOW AND ICE DATA CENTER, UNIVERSITY OF COLORADO

Dr. Deems discussed the need for improved SWE estimates, as well as shortcomings in current snow monitoring methods. He noted that the current operational paradigm relies on sparse measurements and the historic record to produce a statistical or index-based snowmelt runoff forecast. This approach includes the assumption that current climatological conditions resemble those of the past, which indicate that forecast errors will increase as current conditions deviate from the historical record. Mr. Deems suggested that new data sources are needed to address this issue and to move towards a physically based hydrology model. To be useful, he said that data sources must provide repeated, spatially explicit maps of snow albedo, snow depth, and SWE. Dr. Deems pointed to the ASO data presented by Dr. Bormann as an example of the type of data that is needed.

Dr. Deems explained that SnowEX is a data source being developed by NASA, which aims to explore the global distribution of SWE and find the best combination of sensing methods (multi-sensors and models) to measure SWE. He said that a key first-year goal was to test and develop snow remote sensing techniques and models in forested environments. This included ground remote sensing, airborne measurements, manual measurements, and in situ measurements. He noted that the large dataset collected in the first year demonstrates that snow depth is the primary factor in the variability of SWE, and indicated the project will eventually contribute to spatially explicit SWE data products integrated through the Weather Research and Forecasting Model Hydrological modeling system that can be used in forecasts by water operators.

Improved Snow Modeling and Data Assimilation to Advance Water Supply Forecasting

Paul Micheletty, Hydrologist

RTI International

Mr. Micheletty discussed research to improve water supply forecasts in the upper Colorado River Basin through the Hydrology Laboratory – Research Distributed Hydrology Model, which differs from the water supply forecasting used by CBRFC. The Hydrology Laboratory – Research Distributed Hydrology Model uses gridded implementation of SNOW-17, a temperature index snowmelt model at a 1-kilometer (km) grid-scale and 6-hour time step. He reported that a process of parameter optimization using penalty functions was completed to determine model parameters in the basins of interest and that RTI International (RTI) developed visualization tools to ensure realistic parameters and hydrographs after model calibration was completed.

Mr. Micheletty explained that the Ensemble Kalman Filter was used to provide an objective framework to produce better SWE estimates, based on uncertainties in observations, and model and forcing data. He noted that RTI generated ensembles of estimated observed gridded SWE in the Colorado River Basin using a six-step process. Remote sensing datasets were used to improve the spatial distribution of observed SWE estimates. Once SWE estimates were obtained, they were fed back into the SNOW-17 model along with the Utah Energy Balance Snowmelt Model to compare performance. Mr. Micheletty reported that initial results show differences in the water balance between these models, adding that RTI is still investigating. He concluded his presentation by noting future work efforts. These include performing a full verification study for water years 1988-2016 using ESP, and implementing the MODDRFS product to improve snow-melt processes in the upper Colorado River Basin impacted by dust on snow.

GENERAL DISCUSSION:

Integrating snow research into existing forecasts was a key discussion topic. Participants from Reclamation indicated that their organization does not have a way to incorporate snowpack data into the forecasts, and indicated that CBRFC would be a more appropriate conduit for using this information. A Reclamation representative suggested running current and alternative methods of forecasts through the same models to track performance and impacts to projected operations.

One audience member expressed concern that the research feels “siloed” and asked how it fits into the CBRFC’s existing toolbox. One of the presenters confirmed that this is a problem and noted that all the projects are actively seeking partnerships to apply the data; they also are looking to forecast improvements relevant to operations. The audience offered another question related to the sensitivity of the forecast to snow, and inquired whether spending resources on snow research was giving agencies the largest amount of forecasting benefit for their dollars. Dr. Bormann replied by providing the details of ASO's partnership with Hetch Hetchy. She indicated that reforecasting in initial years improved forecast error from 24 to 30 percent down to 15 percent. She offered that snow is the most important component of inflow forecasting and said that ASO should be used more in an operational forecasting setting, such as the one discussed.

Some participants questioned the feasibility of using ASO methods on a larger scale and inquired whether it is cost prohibitive to conduct multiple ASO flights to map one large basin. Dr. Bormann offered that the cost of ASO flights is small compared to a 30-40 percent reduction in forecast error that could result from not having the ASO data. The audience also inquired about the proposed space-based satellite imagery project discussed. Dr. Bormann replied, estimating a 20-year time horizon on the NASA satellite launch and indicated that there would be a need to replace the satellite every three to five years. She added that optimal resolution of the space-based data still needs to be decided on by community consensus, but will range from 3 to 50 meters (most likely around 10 meters).

SESSION 3: IMPROVING MID-TERM METEOROLOGIC FORCING

KEY THEMES:

- Accurate seasonal streamflow forecasting addresses both hydrologic and meteorological uncertainty
- Seasonal forecasting can still miss large events such as the 2015/2016 ENSO and the Miracle May

PRESENTATIONS:

ADVANCING FLOW PREDICTION USING THE HYDROLOGIC ENSEMBLE FORECAST SERVICE (HEFS) MODEL

JOHN LHOTAK, DEVELOPMENT AND OPERATIONS HYDROLOGIST

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, COLORADO BASIN RIVER FORECAST CENTER

Mr. Lhotak provided an overview of two meteorological models that were incorporated into CBRFC streamflow forecast models: the Global Ensemble Forecast System (GEFS) and the Climate Forecast System (CFSv2). GEFS is a short-term (15-day) forecast model and CFSv2 is a long-term (9-month) forecast model; both simulate precipitation and temperature minimum and maximum at 1-degree gridded resolution. He explained that reforecasts from these models were fed into a Meteorological Ensemble Forecast Processor (MEFP), along with historical observations of precipitation and maximum/minimum temperature in the Colorado River Basin, to develop parameters for use in the forecast process. In both models, temperature maximums showed the most forecasting skill. Temperature minimums showed some skill, and precipitation showed no skill.

Mr. Lhotak explained that meteorological forcing from these models were used in ESP to simulate 30 traces of streamflow, measured by standard mean daily flow. This process is called the Hydrological Ensemble Forecast Service (HEFS). Analysis of HEFS results indicated very little, if any, skill added with GEFS/CFSv2 forecasts. Mr. Lhotak concluded his presentation by noting the need for more analysis on a monthly scale, as well as exploration of GEFS temperature forecast's ability to improve runoff timing.

APPROACHES FOR IMPROVING PREDICTABILITY IN OPERATIONAL SEASONAL STREAMFLOW FORECASTING: LESSONS LEARNED

DR. ANDREW WOOD, PROJECT SCIENTIST III

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH, RESEARCH APPLICATIONS LABORATORY

Dr. Wood provided an overview of changes to seasonal streamflow predictability and noted that there are multiple potential strategies for improving hydrologic and streamflow forecast systems. The two major sources of predictability include hydrological predictability coming from water stored inside the watershed, called Initial Hydrological Conditions; and meteorological predictability, or knowledge about the future weather and climate (such as through Seasonal Climate Forecasts). For snow-driven basins in the western United States, he noted that cold period (winter) forecast skill depends mostly on hydrological predictability, because precipitation is falling as snow rather than driving runoff, and the warmer snowmelt period forecast skill depends on both Initial Hydrological Conditions and on meteorological predictability, because variations in spring weather and climate modulate runoff amounts and timing.

Dr. Wood suggested several ways to improve hydrological predictability moving forward. These include using new hydrological observations and meteorological analysis techniques, improving watershed modeling, hydrological data assimilation, and greater use of verification. He pointed to climate predictability as another important aspect of streamflow forecasts and noted various methods for examining meteorological predictability. These include the use of statistical climate indices and custom analyzed climate-system variables that are downscaled to local watersheds.

Above all, Dr. Wood stressed the critical need for systems and approaches that can support hindcasting, which enables verification, testing of alternative, new approaches, and skill analyses to inform hybrid approaches that may combine multiple types of predictions (both statistical and model-based, or dynamical). Such hybrid approaches have lately been found to be more robust due to leveraging the strengths of both statistical and dynamic predictions from multiple sources. He argued that truly "hindcastable," reproducible methods are key to improving predictions in the long term; they benchmark improvements and can offer more flexibility in merging multiple sources of predictability.

Improving Subseasonal to Seasonal Precipitation and Temperature Prediction Capability

Dr. Nathaniel Johnson, Associate Research Scholar

Princeton University, Atmospheric and Ocean Sciences

Dr. Johnson discussed sources and mechanisms of subseasonal to seasonal weather and climate predictability. He indicated that one of the greatest challenges was bridging the gap between short-term weather predictions and longer-range seasonal predictions, specifically the week three and four forecasts. He offered that week three and four temperature can be partially explained by the Madden-Julian Oscillation, which is used in conjunction with the El Niño/Southern Oscillation (ENSO) and linear trend to produce skillful forecasts. He noted that the NOAA Climate Prediction Center (CPC) started to produce outlooks for weeks three and four based on statistical guidance from Madden-Julian Oscillation/ENSO and dynamic guidance from models such as CFSv2, European Centre for Medium-Range Weather Forecasts, and Japanese Meteorological Agency model. While these forecasts were deemed to be skillful over the contiguous United States for temperature, the models performed poorly in predicting precipitation, particularly over the southwestern U.S., during the large El Niño event of 2015/2016. He noted that statistical forecasts of teleconnection pattern indices were developed and linked to temperature/precipitation to improve winter temperature forecasts.

Dr. Johnson also discussed improvements in dynamical model research and predictions at the Geophysical Fluid Dynamics Laboratory. He discussed the merits of three models with differently sized atmospheric grid cells (200 km, 50 km, 25 km) and noted that the higher resolution models captured the spatial gradients of precipitation over the western U.S. much better than the lowest resolution model. The higher resolution models also did a much better job in simulating the North American monsoon during the months of July through September. He said that the most predictable global seasonal precipitation pattern in the Forecast-oriented Low Ocean Resolution model (50-km resolution) shows much more prediction skill than in the lower resolution (200 km) Geophysical Fluid Dynamics Laboratory CM2.1 model. However, none of the model forecasts were able to capture the western U.S. precipitation during the 2015/2016 El Niño event. Regardless, Dr. Johnson indicated that improvements in global climate models have yielded improved seasonal forecasts of temperature and precipitation, and that these are used as part of the North American Multi-Model Ensemble.

GENERAL DISCUSSION:

Forecast information and messaging was an important topic in this discussion. Attendees pointed towards 2015/2016 ENSO predictions and stressed the importance of accuracy to stakeholders. Presenters explained that the inaccurate prediction may be attributable to atmospheric variability or land-atmospheric interactions that are/were not understood. Rather than addressing specific prediction accuracy improvements, presenters stressed the need of proper communication of uncertainty in forecasting. One presenter suggested that the 2015/2016 ENSO uncertainty was available, but was not properly messaged to the public or to water managers.

One attendee asked when predictions should be made, and why they are popularized for a mass audience. The presenters noted that a few official outlets communicated information in a simplistic way and that many of them talked about the uncertainty. While there was no consensus for when predictions should be made, participants agreed that better communication is needed.

Session 4: Overview of Colorado River Simulation System

KEY THEMES:

- CRSS is the primary long-term water planning tool for the Colorado River Basin
- Upper and lower basin stakeholders use CRSS for different purposes, but agree on use of CRSS as a testbed for policy discussion

PRESENTATIONS:

Introduction to Colorado River Simulation System

Alan Butler, Hydrologic Engineer

U.S. Bureau of Reclamation

Mr. Butler provided an overview of CRSS, Reclamation's long-term planning model that simulates basin-wide river and reservoir conditions over decades. He noted that CRSS projections are used to support long-term planning decisions, such as the development of new operating criteria and guidelines. At least two official model simulations are made each year, in January and August.

The model uses assumptions and inputs including future natural inflows, future water demands, future operations, and initial reservoir conditions. Mr. Butler indicated that future natural inflows have the greatest effect on results, and that these can be generated through a number of methods (Colorado River Basin Water Supply and Demand Study [Reclamation, 2012]), including: Observed Resampled, Paleo Resampled, Paleo Conditioned (combination of paleo and observed data), and downscaled General Circulation Model (GCM) projected (natural flow developed by forcing a hydrology model with downscaled future climate projections). Each future natural inflow methodology, i.e., scenario, includes hundreds of individual streamflow sequences to help account for future hydrologic uncertainty. He noted that future water demand is represented in the model by approximately 500 demand nodes, and discrete scenarios are developed to address uncertainty associated with future demand. Mr. Butler noted that evaporation rates, outdoor municipal demand, and agricultural demand are adjusted to account for climate change in the Downscaled GCM Projected scenario (Reclamation, 2012).

CRSS gives monthly and annual flow output for individual traces, i.e., a single CRSS run with one streamflow sequence from a future natural flow scenario, and statistics can be computed across all traces in a scenario. Mr. Butler explained that consumptive use is also given by state, basin, sub-basin, and user in the Lower Basin. He noted limitations on the validity of output results, particularly in extreme low-flow situations in the Lower Basin due to modeling assumptions associated with shortages beyond those provided in the Interim Guidelines (Reclamation, 2007) that are necessary when Lake Mead runs out of water. He added that future and ongoing work related to CRSS is aimed at exploring additional water supply scenarios, including updating the Downscaled GCM Projected supply scenario to reflect newer CMIP5 projections, as well as enhancements to improve modeling of reservoir operations and water use.

The Importance of CRSS Projections to Stakeholders

Colby Pellegrino, Director of Water Resources, Southern Nevada Water Authority

Chuck Cullom, Colorado River Programs Manager, Central Arizona Project

Eric Kuhn, General Manager, Colorado River District

Ms. Pellegrino discussed key differences between the upper and lower Colorado River basins. She offered that Upper Basin water users are more accustomed to variability, given their geography and proximity to storage, while Lower Basin users have more warning of and time to prepare for shortages. She said that the Southern Nevada Water Authority usually plans for shortages rather than surpluses, but that the agency considers the possibility and/or likelihood of both.

Ms. Pellegrino said the most important aspects of modeling for her organization are repeatability of results and transparency. She acknowledged that introducing variability into models may produce more realistic results, but noted that the results are not repeatable. She suggested variability be embedded into model inputs, rather than the model rule structure, which is more likely to provide the right balance of repeatable and realistic results.

Mr. Cullom discussed the use of CRSS in Central Arizona Project decision-making. He said that there is a significant benefit of having a set of tools that all the stakeholders in the Colorado River system agree on for policy discussion. He praised the large community of CRSS users, noting that every agency has the ability to contribute to the discussion, and to use CRSS internally to advance discussions. Mr. Cullom noted that the Central Arizona Project used CRSS during the 2013-2014 discussion between the basin states about risk on the Colorado River system. He said that CRSS has allowed for better decision-making based on risk and vulnerability, shared between agencies and stakeholders.

Mr. Kuhn discussed how the water planning paradigm has changed over time, noting that CRSS has moved the paradigm in water planning from that of legal certainty to water certainty, particularly considering climate change factors. He stressed the differences between the upper and lower basins and said that the Upper Basin is mostly concerned with water levels at Lake Mead and Lake Powell. Mr. Kuhn said that the Colorado River District examined how the Colorado State Model and CRSS can inform each other.

Mr. Kuhn expressed concern that policy and science are mostly focused on the supply side of water planning, and suggested that demands need more attention. He acknowledged that there is often reluctance to discuss demands, but suggested that focus on the technical side of this issue is likely to reduce political tensions.

GENERAL DISCUSSION:

Participants discussed the topic of a shortage declaration, which has not yet materialized as expected/forecasted, based on Lake Mead water levels. One attendee wondered if investigation could help to determine what went wrong, and if this information could be used to improve the CRSS model. Ms. Pellegrino responded that the 2007 guideline has not been re-run to figure out what went wrong, but offered that CRSS projections don’t reflect near-term operational decisions intended to prevent shortage, such as storing water in Lake Mead. Further, she invited symposium attendees to consider the consequence of planning for a shortage that doesn’t come versus not planning for a shortage that does. Another participant said that agencies need to recognize what probability means. He underscored the need for understanding that there will always be a risk of shortage.

Participants also discussed CRSS model resolution. One attendee noted that assumptions embedded in the model, such as spatial and temporal resolution, are carryovers from the development of CRSS in the 1970s. He wondered if finer resolution would yield better model results and noted that CRSS does not include smaller reservoirs, which makes it difficult to simulate Upper Basin demand. A panelist acknowledged the desire for additional detail, but noted that the water supply decision is based on Lake Mead elevation. Another attendee voiced concern for the lack of resolution being a technical limiting factor in developing policy. A Reclamation participant responded, suggesting that resources can be used elsewhere. He explained that as long as CRSS accurately simulates Lake Powell and Lake Mead, the model is doing what it is meant to do. For some participants, incorporating demand is an important factor in model performance and was recommended as a worthy future work effort.

Session 5: Bridging the Forecast and Long-Term Projection Gap

KEY THEMES:

- Future projections currently depend on probabilistic traces of historical climate and hydrology
- New methods, such as decadal predictions and stochastic weather generators, can help decision making on an appropriate time horizon

PRESENTATIONS:

MTOM to CRSS: Transition and Comparison

Dr. James Prairie, Hydrologic Engineer

U.S. Bureau of Reclamation

Dr. Prairie detailed work by Reclamation in January 2017, to bridge the MTOM and CRSS models: the MTOM model was used to project 2017 operations using 35 future inflow sequences. CRSS was then initialized with each of the MTOM projections, and was used to project 2018-2026 conditions using 107 hydrologic inflow sequences from the observed natural flow record. Dr. Prairie reported that a total of 3,745 CRSS simulations were computed and analyzed to produce a five-year table that was used to examine the probability of shortage and surplus.

Dr. Prairie said that a streamflow forecast testbed was used to explore MTOM and CRSS results. Major hydrology metrics tested include inflow forecast skill 24-months out, and shortages and surpluses in Lake Mead and Lake Powell. He noted that these results indicate that initial conditions are crucial to future projections. He offered that the ESP forecast that drives MTOM doesn't show skill in far out years compared to natural flow, but improves closer to the current month. Dr. Prairie said that next steps in this analysis include blending these models on the operations side and further exploring the differences between ESP and natural flow streamflow forecasts.

Toward the Application of Decadal Climate Predictions

Dr. Erin Towler, Project Scientist

National Center for Atmospheric Research

Mesoscale and Microscale Meteorology Laboratory

Dr. Towler presented work done by NCAR to produce decadal predictions that bridge the gap between seasonal forecasting and long-term climate change projections. She noted that decadal predictions are initialized to current conditions then run out to 10 years, much like seasonal climate forecasts. Dr. Towler said that skill in these probabilistic predictions is largely regionally dependent on the Pacific Decadal Oscillation and Atlantic Multidecadal Oscillation phases.

Dr. Towler explained that the Understanding Decision-Climate Interactions on Decadal Scales framework was developed to understand the role decadal climate predictions have in water management decisions. She said that the 1980-2010 NCAR CCSM4 temperature hindcasts were first evaluated across the contiguous U.S. using Anomaly Correlation and mean-squared skill score. Then, the 2010 hindcasts were manipulated to examine the 2011-2015 prediction period to compare against observed data. Finally, the predictions were translated to individual case study watersheds using the Delta T, Weighted Resample, and Hybrid methods.

Dr. Towler reported that all three translation methods do a better job than climatology at predicting future weather. She offered that this work, while still experimental, provides a framework that water managers can use to get systematic alternatives to climatology. She concluded her presentation by noting that current work efforts are focused on using translated decadal temperature predictions in the Water Evaluation and Planning System hydrologic model to estimate inflows into a Colorado reservoir to make these predictions more relevant to water managers.

Conditional Stochastic Weather Generator for Seasonal (to Multi-Decadal) Simulations

Dr. Balaji Rajagopalan, Professor and Chair

Department of Civil, Environmental, and Architectural Engineering

University of Colorado Boulder

Dr. Rajagopalan introduced a stochastic weather generator developed at the University of Colorado, Boulder in collaboration with the Co-operative Institute for Research in Environmental Sciences. He said the research was motivated by the need for ensemble weather scenarios to properly capture uncertainty in the climate system, and offered that synthetic ensemble scenarios of daily weather based on historical data are required for efficient water resources planning and management. The project included a parametric weather generator that produces occurrence, rainfall amount, Tmax Tmin, and the dependence between precipitation and temperature. He said that a K-Nearest Neighbor time series bootstrap method was also developed to resample the nearest neighbors to target values to generate ensembles. Another method explored was the Generalized Linear Model based weather generator, wherein specified distributions of the response variable Y are modeled at each location. He offered that seasonal simulations can be conditioned on climate forecasts, and captures the observed variability well. He added that multi-decadal simulation can be used to examine climate change, where unconditional simulations repeat the climatological cycle and conditional simulations are consistent with the projections.

Dr. Rajagopalan noted that these methods have been applied to agriculture management, crop modeling, and seasonal and multidecadal planning studies. For example, hydrologic forecasting work was completed for Java Island in Indonesia, where the ensemble flow forecast generated for the 2001-2010 period proved skillful in modeling the streamflow conditioned on climate forecast. Another application of this technology was completed for the San Juan Basin in the Colorado River Basin. The K-Nearest Neighbor stochastic weather generator was applied to ESP and hydrologic forecasting in this basin. Dr. Rajagopalan said the threshold exceedances probabilities in this work reflect the seasonal forecast; weather generator-ESP shows a higher probability of exceedance than ESP. Overall, he concluded that weather generators enable the simulation of weather sequences conditioned on seasonal and multidecadal climate projections, and this method can be used as an effective downscaling technique to capture uncertainty in future climate.

GENERAL DISCUSSION:

Uncertainty was a key discussion topic for this session, particularly in the context of what uncertainty means to future climate projections. A participant made the distinction between variability and uncertainty, noting that variability implies that the cause of difference is known, whereas uncertainty implies unknown causes. Dr. Prairie explained that further refinement of projections is not adding uncertainty to the modeling problems, but revealing uncertainty that was already there. He added that rather than aiming to decrease the range of variability, Reclamation is looking to have more confidence in that range. He suggested a probabilistic approach in presenting results, and providing minimum and maximum in results, so that extremes can be more effectively explained.

Another aspect examined is how Reclamation projections can be weighted to reflect future weather trends. A participant stated that Reclamation is doing work to explore warmer weather projections, including taking a subset of record to look at the worst-case scenario, and taking subsets of more recent years that include warming trends. A CBRFC representative suggested that weather-generation techniques such as those presented by Dr. Rajagopalan are promising, and offered that ENSO years in traces should not be separated out. Dr. Rajagopalan added that 35 years of historical data does not provide enough traces, especially of ENSO years, to accurately predict future weather and weather generators are the future.

Session 6: Improving Long-Term Hydrologic Projections Used in Planning

KEY THEMES:

- Understanding uncertainty in future projections is key to translating science to water-related decision-making
- Distillation of scenarios/projections into "hydrologic storylines" is useful for water resources planning

PRESENTATIONS:

Colorado River Streamflow Sensitivities: Evaluating Sources of Uncertainty in Projections of Long-Term Streamflow

Dr. Julie Vano, Project Scientist I

National Center for Atmospheric Research, Hydrometeorological Applications Program

Dr. Vano discussed why there is such a wide range of projections of future climate change impacts on Colorado River streamflow. Citing numerous studies, she detailed multiple approaches to generate future streamflow projections and identified four sources of uncertainty in these methodologies: Global Climate Model (GCM) and emission scenario selection; spatial scale and topographic dependence of climate change projections; land surface representations; and downscaling methods. She stressed the value of a comprehensive approach that includes both paleoclimate reconstructions and future projections. She also noted a dichotomy between how climate science advances using different approaches that aren't easy to reconcile and planner's preference for explicit characterizations of uncertainty. Dr. Vano offered that her paper (Vano et al., 2014) aims to bridge this gap by synthesizing past studies and providing insights on where there is consensus on future trends for use by decision-makers.

Dr. Vano noted that ongoing research (see https://ral.ucar.edu/hap/computational-hydrology) is directed towards building bridges between research and application. She offered that key bridges include usable products, appropriate guidance, and effective feedback on modeling tools. Both research and management communities benefit from better understanding each other's needs and leveraging each other's expertise. A new set of guidelines, "Dos and Don'ts for using climate change information in water management," is being developed with the goal of facilitating this exchange.

Hydrology Model Selection and Calibration: Impacts to Streamflow Projections

Dr. Ethan Gutmann, Project Scientist II

National Center for Atmospheric Research, Hydrometeorological Applications Program

Dr. Gutmann emphasized uncertainty in each step of the streamflow modeling chain, but focused more on specifics within hydrology models. He presented the Structure of Unifying Multiple Modeling Alternatives (SUMMA) as a method of defining a single set of conservation equations for land biogeophysics. He explained the SUMMA method allows different spatial discretizations, time stepping schemes, and model parameterizations to be tested in the same framework. The method conceives of the model as stages with progressively more uncertainty: starting with water and energy conservation equations that comprise a numerical solution, then physical processes that encompass modularity at the level of individual fluxes, then model options for each process.

Dr. Gutmann said that a key challenge was scaling models from use in individual basins to applicability across hundreds of basins. He noted that to direct work towards the process variables that matter the most, work was done to explore which attributes of catchments have the most influence on dominant hydrological processes. He reported that the most information was seen in climate variables, and the least in soil variables. Interestingly, a physical hydrology model and a statistical machine learning model provided similar skill in their estimates of signatures of hydrological behavior. In addition to uncertainty in hydrologic model equations and parameters, uncertainty in climate downscaling approach was also discussed. While statistical downscaling methods were shown to have similar apparent skill in current climate as dynamical methods, they were also shown to sometimes have a different climate change signals; it was suggested that this is due to the stationarity assumptions inherent in the statistical methods. In contrast, dynamical downscaling methods are likely to be more reliable in their change signal, but are computationally expensive and may not represent current climate statistics as well at individual locations.

GENERAL DISCUSSION:

Much of the session discussion was centered on the role that science messaging plays in decision-making. One participant asked if participants had any ideas to make the science “more satisfying” for decision-makers. This prompted multiple responses: one participant offered that water managers have been making decisions in the face of uncertainty for a long time, and that this is unlikely to change as the science related to planning will never be “complete.” Another participant indicated that modeling scenarios tests a system to reveal vulnerabilities, but that modeling informs water planning in the same way Factors of Safety are accounted for in soil structure calculations. Participants cited multiple accounts of science messaging through the media (drought projections, etc.) and noted the challenge of communicating with the public when actual conditions do not materialize as projected.

There were also specific questions about parameterization, as discussed by the presenters. A participant pointed out the need for geophysical parameters (including land cover change, and vegetation growth and response) in hydrology models to change over time as the Earth changes. An audience member offered that parameter estimation in these models, despite decades of progress, is insufficient in light of model uncertainty. Another participant indicated parameter ensembles in the models are more important than getting one particular parameter correct, and that this was dependent on which impact the model was being simulated to analyze. Participants agreed that dynamical hydrological modeling is the future of science and that more funding should be directed towards computing power. However, participants were reluctant to claim that dynamical modeling will reduce uncertainty.

SESSION 7: INFLUENCE OF TEMPERATURE ON STREAMFLOW

KEY THEMES:

- Temperature can be used to explain trends in streamflow that precipitation does not
- Warmer temperatures affect basin-wide streamflow during times of both high and low flow

PRESENTATIONS:

EVALUATING THE INFLUENCE OF AIR TEMPERATURE AND SOIL MOISTURE CONDITIONS ON COLORADO RIVER STREAMFLOW

DR. CONNIE WOODHOUSE, PROFESSOR

SCHOOL OF GEOGRAPHY AND DEVELOPMENT, UNIVERSITY OF ARIZONA

Dr. Woodhouse presented work done by the Laboratory of Tree-Ring Research at the University of Arizona to investigate the effect temperature has on Colorado River streamflow. The study used 1906-2012 Parameter-Elevation Regressions on Independent Slopes Model climate data for the upper Colorado River Basin, modeled monthly soil moisture storage capacity, and natural flow estimates for the Colorado River at Lees Ferry. This research was centered on four questions, including:

- What are the roles of precipitation, temperature, and prior fall soil moisture in Colorado River annual streamflow?
- Do temperatures play a role in reducing or enhancing flows?
- What role does temperature play during droughts?
- Is temperature becoming more influential as warming has occurred?

Dr. Woodhouse reported that a statistical model was used to identify the most important climatic factors that explain water year streamflow. Results indicated that October through April precipitation explained 66 percent of the variance, March through July temperature explained 8 percent, and November soil moisture explained 2 percent. Using only the past 50 years of data yielded roughly the same results.

Dr. Woodhouse noted that the runoff season temperature explained a larger proportion of streamflow variance during years when flow was greater or less than what was anticipated given actual precipitation. For example, when Upper Basin precipitation is 180 percent above normal for the year, streamflow is expected to also be about 170 to 180 percent of normal flow. By analyzing only those years when precipitation yielded streamflow that was different than expected, Dr. Woodhouse reported that years with flows higher than anticipated relative to precipitation tend to be cool. Those years with flows lower relative to precipitation tend to be warm. Dr. Woodhouse said that tree-ring reconstruction from 1569 to 1997 was used to provide a longer-term context than the datasets in the earlier statistical analysis, and indicated a higher number of above-average flow years with warm spring conditions in the 20th century, compared to past centuries.

Dr. Woodhouse indicated that both temperature and precipitation have had variable influences on flow in past droughts. Warmer temperatures were seen to have a larger influence on droughts, as precipitation was relatively large during the past two historical droughts of 1988-1996 and 2000-2012. This research indicates the effect that increasing temperatures are having on Colorado River Basin streamflow. Dr. Woodhouse said that next steps in this research include exploring the role of antecedent moisture in upper Colorado River Basin streamflow, but noted that the current thinking is that wet fall conditions may increase streamflow efficiency.

Developing Synthetic Streamflow Time Series Using Precipitation and Temperature

Dr. Stephanie McAfee, Assistant Professor

Department of Geography, University of Nevada, Reno

Dr. McAfee explored the production of synthetic streamflow time series using identical projections of temperature and precipitation. She discussed the development of a statistical model to derive naturalized water-year flows at Lees Ferry using previous October-April precipitation, May-September precipitation, May-July temperature, and previous water-year flows. Each of the decision variables in the model was weighted according to its importance. In all, 500 iterations of the model were run, using 125 different combinations of mean climate change.

Dr. McAfee reported the results of this analysis, which indicate mean flow is lower under warmer/drier conditions, but that variability is high. She concluded that initial conditions were crucial in determining mean flow, and that variability of the input climate data had a large effect on drought frequency. Dr. McAfee said the outcomes of this study are clear: similar climate scenarios can produce very different future flows, yet distinct climate scenarios can produce nearly identical future flows. She stressed the importance of where the science community uses its limited computing resources and acknowledged that many climate models yield the same answer.

The Influence of Temperature on Runoff Efficiency: Implications for Streamflow Forecasting

Dr. Flavio Lehner, Postdoctoral Fellow

National Center for Atmospheric Research, Research Applications Laboratory

Dr. Lehner presented work done on the effect of temperature on streamflow forecasting in the Upper Rio Grande and upper Colorado River basins. He noted that forecast skill is mediocre prior to the critical allocation deadline in April, and that there is anecdotal evidence of systematic forecast biases in recent years. He explained the goals of this research was to find the cause of systematic forecast bias and to then improve the forecasts based on lessons learned. He noted a steep downward trend in runoff ratio over the last 30 years, based on a reconstruction of historical streamflow and precipitation from 1575-1977. Dr. Lehner explained that temperature and precipitation anomalies in each year of streamflow were tallied and correlated for the observed (1943-2015 Current Era), the reconstructed (1571-1977 Current Era), and the Community Earth Systems Model control datasets (1,800 years). The correlation between these anomalies revealed that a very low runoff ratio is two and a half- to three-times more likely when temperature is above-median than when it is below.

Dr. Lehner explained that this knowledge was applied to improve seasonal streamflow forecasts using the North American Multi Model Ensemble (NMME). These seven U.S. climate models were initialized every month and run out for 12 months to produce seasonal forecasts of temperature and precipitation.

Dr. Lehner concluded his presentation by saying that temperature anomalies were not common trends, but offered that temperature does act to make low runoff ratio years even lower.

GENERAL DISCUSSION:

Participants discussed the implications of temperature research on drought. One attendee noted that hot droughts are much more detrimental than cool droughts, and asked what the important ecosystem thresholds are during these drought periods. One panelist suggested the need for a technical committee to track measured parameters in basins and act on them as they happen, with different action points based on the ecosystems that each agency oversees. Dr. Woodhouse added that ecosystem affects should be examined at discrete watersheds levels, where antecedent conditions are different. She noted that after a time horizon of 10 to 15 years, ecosystem questions become difficult to answer. This is because trees are most stressed during drought and that information obtained from tree rings is mostly about summer time temperature, when most tree growth occurs.

Incorporation of temperature into water resources planning was also described in this discussion. An attendee asked to what extent water managers are paying attention to May and June temperatures and how this correlates with planning efforts. A panelist replied that the tools have not advanced enough to accomplish this; the models used are very complicated and are not commonly applied to separate out specific temperature effects in particular areas. They noted that while quantitative planning is not possible, water managers must be aware that hot year droughts are more stressful than cool year droughts. Another attendee asked about the possibility of physical models to replace the statistical models presented in the talks. A panelist responded that hydrological models that use the effects of temperature exist. They noted that this statistical work mostly reveals uncertainties in the forecast, and emphasized even the most sophisticated models disagree on the sign of streamflow change.

Session 8: Influence of Evapotranspiration and Evaporation Estimates on Long-Term Demand Projections

KEY THEMES:

- Hydrological models with built-in ET modules have been used to examine climate change effects on long-term demand
- Evaporation estimation methods should be selected on a case-by-case basis due to different strengths and weaknesses

PRESENTATIONS:

Estimating Irrigation Demands and Reservoir Evaporation Demand for Climate Change Risk Assessment

Mark Spears, Hydraulic Engineer

U.S. Bureau of Reclamation

Mr. Spears presented research conducted by Reclamation in collaboration with DRI to estimate irrigation water demand and reservoir evaporation under future climate change. The research results are included in the *West-Wide Climate Risk Assessments (WWCRA): Irrigation Demand and Reservoir Evaporation Projections* report (Reclamation, 2015). Mr. Spears explained that 1/8-degree gridded climate data for both historical and future periods (Bias-Correction Spatial Downscaling and Coupled Model Intercomparison Project) was used to force irrigation water demand and reservoir evaporation models in Reclamation's eight major river basins for three future time periods: 2010-2039, 2040-2069, and 2070-2099. Five climate scenarios utilizing an ensemble informed hybrid delta method were used for forcing the ASCE-Penman Monteith dual crop coefficient model (ET demands). The Complementary Relationship Lake Evaporation (CRLE) model was then used to simulate open water evaporation from 12 reservoirs/lakes in the study basins, including Lake Powell and Lake Mead. Using these methods, spatial maps were produced to show the distribution of temperature change, precipitation change, baseline ET change, crop ET change, and net irrigation water requirement change. Mr. Spears reported that Lake Powell and Lake Mead showed high variability in precipitation, as well as increasing temperature and net evaporation trends.

Mr. Spears also discussed Reclamation's *Colorado River Basin Water Supply and Demand Study* (Reclamation, 2012). This study projected water supply and demand in the basin over a 50-year period under climate change. The Variable Infiltration Capacity (VIC) model was used to calculate climate change factors used in scenario-specific irrigation demands and evaporation estimates. The VIC model was used to estimate Penman Monteith-based potential evapotranspiration (PET), and was combined with precipitation data from Coupled Model Intercomparison Project to obtain gridded PET irrigation demand change factors. Mr. Spears said the study points towards increased PET by late-century, especially in the summer months. He explained that reservoir evaporation baselines used CRSS values and then applied change factors based on VIC PET for open water.

Mr. Spears concluded that both research studies show varying amounts of increased irrigation demands and reservoir evaporation levels, with the WWCRA methodology showing significantly higher increases.

He added that neither study included the carbon dioxide effects on plant transpiration, and suggested this as an opportunity for future work.

Estimating Reservoir Evaporation: Current Practice and State-of-the-Art

Dr. Kathleen Holman, Meteorologist

U.S. Bureau of Reclamation

Dr. Holman discussed the importance of understanding evaporation loss, a critical measure for reservoir accounting and operations, but suggested this factor is among the most difficult to quantify. She described techniques to measure open water evaporation, including indirect techniques such as pan evaporation and water body/energy balance, as well as direct techniques such as the Eddy covariance method.

Dr. Holman provided a detailed explanation for two methods: the CRLE Model and the Eddy covariance method. She explained that the CRLE Model is a combined approach for practical and operational estimates of evaporation. This model requires monthly estimates of solar radiation, air temperature, and dew point temperature to produce albedo, emissivity, water temperature, heat storage, and evaporation estimates. She offered that the CRLE model is widely used, but has limitations: for example, it does not account for advected heat from inflow and outflows, and it also does not consider freezing conditions. Dr. Holman also discussed the Eddy covariance method and explained that this common direct method measures turbulent exchange at the air-water surface to estimate evaporation. This method, she said, produces the most accurate estimates of evaporation, given suitable environmental conditions and experimental design.

Dr. Holman commented on the varying effectiveness of approaches based on the ability to acquire measurements, the size and shape of water bodies, and the required timescale and accuracy. She offered that future needs for reservoir evaporation research include collecting consistent long-term measurements, establishing a coordinated observation network, improving the representation of reservoirs in atmospheric-hydrologic models, and continued collaboration between research and water management communities.

GENERAL DISCUSSION:

Participants discussed the importance of evaporation data used in water allocation models, particularly seasonal or monthly estimates. Spatial variability of evaporation estimates was also of interest. Multiple attendees questioned if the direct techniques detailed by Dr. Holman had issues with determining evaporation differences across large lakes. She replied that direct methods were not the best choice for larger bodies of water. Further, Dr. Holman indicated that variability in water surface temperature and wind speed are good indicators in any reservoir for the variability in evaporation.

Participants also discussed uncertainty in evaporation estimates. The participants generally agreed there is a need for an uncertainty propagation analysis with the energy budget approach to improve understanding of uncertainty. Participants also noted uncertainties related to instrumentation approaches.

Some participants expressed interest in the current state of plant ET science in light of a carbon dioxide-rich atmosphere. This phenomenon is not currently being accounted for in many ET models, but is in the process of being incorporated. Most of the work previously done to evaluate these changes was performed in controlled greenhouse environments as opposed to in situ studies. Recent knowledge of the significance of this phenomenon have made this gap in the modeling impossible to be ignored.

Recommendations and Next Steps

The Colorado River Hydrology Research Symposium provided a unique summary assessment of the state of the research and application related to Colorado River hydrology. Many important climatic, hydrologic, and operational forecasting research approaches were presented and discussed during the symposium. These topics will remain of high importance as researchers, stakeholders and water managers contemplate and respond to the difficult challenges of climate uncertainty and climate change in the Colorado River Basin over the years to come.

Recognizing the need for ongoing dialogue and action, symposium participants indicated support for the following actions:

- Continue to host an annual or biannual symposium that builds upon the success of the 2017 Colorado River Hydrology Research Symposium.
- Support and improve information sharing between research and application by working to establish an information-sharing network that brings focused research to the broader Colorado River community.
- Develop priority hydrology research areas and identify opportunities to advance research through coordination and/or funding.
- Improve organization of research into areas such as climate, streamflow, snow, soil moisture, and demands; improve the assessment of importance of the research for short-term (3 to 24 months), mid-term (2 to 10 years), and long-term (10 to 50 years) management decisions.
- Identify research areas, or model improvements, that could increase performance of hydrologic assessments with little investments.
- Develop and/or update a document that describes the state of the science, similar to Appendix U of the Final Environmental Impact Statement – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead (Reclamation, 2007)

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Appendix 1. Symposium Presentations
(Presentation titles include link to specific presentation material)

Session 1: Data and Models Used in Seasonal Streamflow Forecasts

Overview of Data and Models used to Develop 24-MS and MTOM Inputs (Lhotak)

Overview of the 24-MS and MTOM (Tighi)

A New Framework to Evaluate the Skill of Different Hydrologic Forecasts (Baker)

Session 1a: Success Story: Research to Applied Science

How the NASA JPL/CBRFC Collaboration Successfully Transferred Research to Applied Practice (Bormann)

From Research to Application: Examples on the Colorado, Rio Grande, and Columbia Rivers (Zagona)

Cloud Computing of Satellite and Gridded Climate Data: From Archives to Answers (McEvoy)

Session 2: Improving Snow Data & Modeling

Using High-Resolution Airborne Snow Observatory Program Data (Bormann)

Assimilation of Multiple Data Sets to Improve SWE Estimates: SnowEX (Deems)

Improved Snow Modeling and Data Assimilation to Advance Water Supply Forecasting (Micheletty)

Session 3: Improving Mid-Term Meteorologic Forcing

Advancing Flow Prediction Using the Hydrologic Ensemble Forecast Service (HEFS) Model (Lhotak)

Approaches for Improving predictability in Operational Seasonal Streamflow Forecasting (Wood)

Improving Subseasonal to Seasonal Precipitation and Temperature Prediction Capability (Johnson)

Session 4: Overview of Colorado River Simulation System (CRSS)

Introduction to Colorado River Simulation System (CRSS) (Butler)

The Importance of CRSS Projections to Stakeholders (Pellegrino, Cullom & Kuhn)

Session 5: Bridging the Forecast and Long-Term Projection Gap

MTOM to CRSS: Transition and Comparison (Prairie)

Toward the Application of Decadal Climate Predictions (Towler)

Conditional Stochastic Weather Generator for Seasonal (to Multi-Decadal) Simulations (Rajagopalan)

Session 6: Improving Long-Term Hydrologic Projections Used in Planning

Evaluating Sources of Uncertainty in Projections of Long-Term Streamflow (Vano)

Hydrology Model Selection and Calibration: Impacts to Streamflow Projections (Gutmann)

Session 7: Influence of Temperature on Streamflow

Evaluating the Influence of Air Temperature and Soil moisture Conditions on Colorado River Streamflow (Woodhouse)

Developing Synthetic Streamflow Time Series Using Precipitation and Temperature (McAfee)

The Influence of Temperature on Runoff Efficiency: Implications for Streamflow Forecasting (Lehner)

Session 8: Influence of Evapotranspiration and Evaporation Estimates on Long-Term Demand Projections

Estimating Irrigation Demands and Reservoir Evaporation Demand for Climate Change Risk Assessment (Spears)

Estimating Reservoir Evaporation: Current Practice and State-of-the-Art (Holman)

APPENDIX 2. COLORADO RIVER HYDROLOGY RESEARCH SYMPOSIUM SPEAKER ABSTRACTS

John Lhotak, Development and Operations Hydrologist

National Weather Service (NOAA),
Colorado Basin River Forecast Center
john.lhotak@noaa.gov

Overview of data and models used to develop 24-MS and MTOM Inputs.

Shana Tighi, Hydrologist

U.S. Bureau of Reclamation
stighi@usbr.gov

Research Interests: Reservoir operations and hydrologic modeling.

Overview of the 24-MS and MTOM.

ABSTRACT: This presentation will provide an overview of the Bureau of Reclamation's Colorado River Basin hydrologic models used for planning mid-term reservoir operations, the 24-Month Study (24-MS) and the Mid-Term Probabilistic Operations Model (MTOM). The 24-Month Study is a deterministic model that is used to provide monthly projections of river operations and reservoir conditions in the 1-2 year planning horizon. It is also used for decision making in the determination of annual reservoir operations. The MTOM is a probabilistic modeling tool that provides information on risk and uncertainty in the 1-5 year planning horizon. This overview will include a comparison of model inputs and a discussion of model uncertainties and performance.

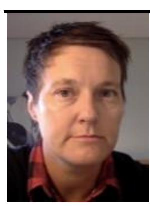
Sarah Baker, Hydrologic Engineer

U.S. Bureau of Reclamation
sabaker@usbr.gov

Research Interests: Hydrologic modeling, streamflow forecasting and global climate models.

A new framework to evaluate the skill of different hydrologic forecasts used in the 24-MS and MTOM.

ABSTRACT: Streamflow forecasts provide information regarding the quantity and timing of streamflow through a river system. Forecasts are used as an input to water operations and planning models such as the Mid-Term Probabilistic Operations Model (MTOM) and the 24-Month Study (24-MS). A skillful forecast, which extends beyond the current year, is valuable to stakeholders who rely on reservoir operation projections to provide skillful shortage and surplus outlooks in the river system. This research seeks to explore options for improving streamflow forecasts and operational projections by establishing a protocol to evaluate skill of experimental forecast methods and operational projections.



Dr. Kat Bormann, ASO Project Scientist / JPL Research Scientist

NASA Jet Propulsion Laboratory,
California Institute of Technology
kathryn.j.bormann@jpl.nasa.gov

Research Interests: Remote sensing; snow hydrology/water resources; spatial and temporal variability; modelling; climatic and short term variability; building operational tools and systems.

How the NASA JPL/CBRFC collaboration successfully transferred research to applied practice.

ABSTRACT: State-of-the-art mapping of fractional snow cover and the radiative forcing effect of dust on snow, as derived from space borne remote sensing data (MODIS 500m spatial resolution), are available in near real-time for much of the western US. These data, produced at the Jet Propulsion Laboratory (JPL), provide up to date information on the condition of the snowpack. Working with the Colorado Basin River Forecast Center (CBRFC), who are responsible for operational streamflow forecasts across the Colorado River basin and the eastern Great Basin, pathways to integrate these remote sensing products into forecasting efforts were developed.

Dr. Edie Zagona, Research Professor

Dept. of Civil Engineering, University of Colorado Boulder
Director, Center for Advanced Decision Support for Water and Environmental Systems
zagona@colorado.edu

From research to application: examples on the Colorado, Rio Grande, and Columbia rivers.

ABSTRACT: One of the main missions of the University of Colorado Center for Advanced Decision Support for Water and Environmental Systems (CASDWES) is to bridge the gap between science and applications in the development of decision support tools for river and reservoir system planning and operations. This talk will describe a selection of specific examples of applications of our R&D results to applications over the past 25 years, especially related to the RiverWare and RiverSMART applications, and end with some guidelines and "lessons learned" in this process.

Dr. Daniel McEvoy, Assistant Research Professor of Climatology

Desert Research Institute
Division of Atmospheric Sciences
daniel.mcevoy@dri.edu

Research Interests: Drought monitoring, climate variability, seasonal prediction, evapotranspiration and evaporative demand.

Cloud computing of satellite and gridded climate data - from archives to answers.

ABSTRACT: Numerous gridded climate, weather, and remote sensing products have been developed to address the needs of both land managers and scientists. However, these data remain largely inaccessible for a broader segment of users given the computational demands of big data. Climate Engine (ClimateEngine.org) is a web-based application that overcomes many computational barriers users face by employing Google's parallel cloud computing platform, Google Earth Engine, to process, visualize, download, and share climate and remote sensing datasets in real-time. An overview of Climate Engine and several examples will be presented that highlight applications specific to the Colorado River Basin.

Dr. Kat Bormann, ASO Project Scientist / JPL Research Scientist

NASA Jet Propulsion Laboratory,
California Institute of Technology
kathryn.j.bormann@jpl.nasa.gov

Research Interests: Remote sensing; snow hydrology/water resources; spatial and temporal variability; modelling; climatic and short term variability; building operational tools and systems.

Using high-resolution Airborne Snow Observatory Program data.

ABSTRACT Addressing the need for improved snow water content estimates in the mountains, the Airborne Snow Observatory (ASO) has been producing high-quality and unprecedented snow water equivalent (SWE) maps from observations at 50m spatial resolution in key basins throughout California and Colorado since 2013. Bridging the research to operational gap has been a primary focus of ASO. In this presentation, we discuss the ASO platform, the automated and tailored products that are produced, and how operational teams are using the data.

Dr. Jeffrey Deems, Research Scientist

CRIES/NOAA Western Water Assessment
National Snow & Ice Data Center, University of Colorado
jeff.deems@nsidc.org

Assimilation of multiple data sets to improve SWE estimates - Snow EX.

Paul Micheletty, Hydrologist
RTI International
pmicheletty@rti.org

Research Interests: Hydrologic modeling, satellite remote sensing applications, snow data assimilation, ensemble forecasting, and model optimization, etc.

Improved snow modeling and data assimilation to advance water supply forecasting.

ABSTRACT: RTI International is working with the Colorado Basin River Forecast Center, Colorado State University, and Utah State University to couple advanced data assimilation techniques with distributed hydrologic modeling to provide improved water supply forecasts for the Upper Colorado River basin. This presentation will focus on our snow data assimilation process and other research components of the project, including model parameter estimation, satellite precipitation data, results with the Utah Energy Balance Snow Accumulation and Melt Model (UEB) versus the conceptual SNOW-17 model, and stakeholder engagement to assess the value of improved forecasts in decision making.

John Lhotak, Development and Operations Hydrologist
National Weather Service (NOAA)
Colorado Basin River Forecast Center
John.lhotak@noaa.gov

Advancing flow prediction using the Hydrologic Ensemble Forecast Service (HEFS) model.

Dr. Andrew Wood, Project Scientist III
National Center for Atmospheric Research
Research Applications Laboratory
andywood@ucar.edu

Approaches for improving predictability in operational seasonal streamflow forecasting - lessons learned.

Dr. Nathaniel Johnson, Associate Research Scholar
Princeton University
Atmospheric and Oceanic Sciences
ncj@princeton.edu

Research Interests: Subseasonal to seasonal climate predictability and prediction.

Improving subseasonal to seasonal precipitation and temperature prediction capability.

ABSTRACT: Advances in subseasonal to seasonal (S2S) climate prediction provide hope for improving operational hydrological forecasting. In this presentation, Dr. Johnson will discuss recent efforts to improve understanding of S2S temperature and precipitation predictability and to develop new forecast products over North America, with a particular focus on the NOAA Climate Prediction Center Experimental Week 3-4 Outlooks. He will consider developments in statistical forecast guidance as well as advances in dynamical forecast models from the Geophysical Fluid Dynamics Laboratory.

Alan Butler, Hydrologic Engineer

U.S. Bureau of Reclamation
rabutler@usbr.gov

Research Interests: Reservoir operations modeling, decision making under uncertainty, long-term planning, data visualization, and modeling ecological flow metrics

Introduction to Colorado River Simulation System (CRSS).

ABSTRACT: CRSS has been the Bureau of Reclamation's long-term planning model since the 1980's. Numerous studies and EIS processes rely on CRSS as the primary basin-wide model of the Colorado River Basin, including the Glen Canyon Dam Long-term Experimental Management Plan EIS, the Colorado River Basin Water Supply and Demand Study, and the Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead EIS. This presentation will describe the CRSS model framework, model assumptions, necessary input, and common output.

Colby Pellegrino, Director of Water Resources

Southern Nevada Water Authority
colby@pellegrino@snwa.com

The importance of CRSS projections to stakeholders.

ABSTRACT: Ms. Pellegrino will discuss the importance of CRSS projections to Southern Nevada stakeholders. In her current capacity, Ms. Pellegrino leads and coordinates development of the SNWA's policies related to the protection of Nevada's interests and rights to Colorado River water. This role requires an extensive knowledge of hydrologic, legal and political issues associated with the Colorado River Basin.

Chuck Cullom, Colorado River Programs Manager

Central Arizona Project
ccullom@cap-az.com

The importance of CRSS projections to stakeholders.

ABSTRACT: Mr. Cullom will discuss the importance of CRSS projections to Arizona stakeholders. At Central Arizona Project (CAP), he works to develop and implement strategic planning efforts and projects that protect and enhance CAP's interests in the Colorado River water supply. Currently, Mr. Cullom is working on plans to develop new water supplies from local, regional, and international projects to augment the Colorado River system. Projects include local and international desalination efforts, snowpack augmentation, Colorado River demand reduction, and conservation efforts. In addition, he leads CAP's participation in the Lower Colorado River Multi-Species Conservation Plan.

Eric Kuhn, General Manager

Colorado River District
ekuhn@crwcd.org

The importance of CRSS projections to stakeholders.

ABSTRACT: Mr. Kuhn will discuss the importance of CRSS projections to Upper Colorado River Basin stakeholders. He began his employment with the Colorado River District in 1981 as an Assistant Secretary-Engineer and has served on the Engineering Advisory Committee of the Upper Colorado River Compact Commission since 1981. From 1994-2001, he served on the Colorado Water Conservation Board representing the Colorado River mainstem. In 2006, Mr. Kuhn was appointed by governor Owens as an at-large representative on the Colorado Interbasin Compact Committee, a position he continues to hold.

Dr. James Prairie, Hydrologic Engineer

U.S. Bureau of Reclamation
jprairie@usbr.gov

Research Interests: Applied research in mid-term operations and long-term water resource planning, climate variability, and decision making under uncertainty.

MTOM to CRSS - transition and comparison.

ABSTRACT: Reclamation relies on the Mid-Term Probabilistic Operation Model (MTOM) and the Colorado River Simulation System (CRSS) to explore uncertainty in basin-wide operational outlooks. MTOM and CRSS can provide one- to five-year outlooks but rely on different dataset and modeling approaches within each tool. Reclamation is exploring these differences and is seeking to objectively report the forecast and operational outlook skill over the one- to five-year period. Exploring the skill should allow stakeholders to consider the strengths and weaknesses of each model and better assess when one model may be preferred over another during decision making.

Dr. Erin Towler, Project Scientist

National Center for Atmospheric Research
Mesoscale and Microscale Meteorology Laboratory
towler@ucar.edu

Research Interests: Climate risks to water quantity/quality/management; increasing the usability of climate information; applications of extreme value theory; statistical modeling and simulation of streamflow.

Toward the application of decadal climate predictions.

ABSTRACT: Decadal climate predictions offer potential to meet planning needs that fall between seasonal forecasts and centennial climate projections. As decadal prediction science advances through its current exploratory phase, there is considerable opportunity to better understand its potential role for water managers. As part of an ongoing NSF-funded project, Understanding Decision-Climate Interactions on Decadal Scales (UDECIDE), Dr. Towler will present a framework towards the application of decadal temperature predictions. The framework is demonstrated using a hydrologic model for a Colorado watershed. Through this case study, the potential benefits and remaining challenges of applying the decadal predictions will be discussed.

Dr. Balaji Rajagopalan, Professor and Chair

Department of Civil, Environmental and Architectural Engineering
University of Colorado Boulder
balajir@colorado.edu

Conditional stochastic weather generator for seasonal (to multi-decadal) simulations.

Dr. Julie Vano, Project Scientist I

National Center for Atmospheric Research,
Hydrometeorological Applications Program
jvano@ucar.edu

Research Interests: Water resource management; hydrology; connecting science and applications; climate impacts.

Colorado River Streamflow sensitivities - evaluating sources of uncertainty in projections of long-term streamflow.

ABSTRACT: Dr. Vano will begin with an overview of various sources of uncertainties in Colorado River streamflow projections based on a synthesis of past studies. This will provide context for discussing ongoing research aimed at exploring these uncertainties in ways that provide resources for both Hydrometeorological research and water management communities. In particular, she will highlight ways this research is being shared, including short accessible summaries, webpages, and guidance on appropriate use – with a goal of promoting more two-way learning between information users and information producers.

Dr. Ethan Gutmann, Project Scientist II

National Center for Atmospheric Research,
Hydrometeorological Applications Programs
gutmann@ucar.edu

Research Interests: Hydrologic modeling, downscaling, uncertainty quantification and alpine snowpack.

Hydrology model selection and calibration - impacts to streamflow projections.

ABSTRACT: The development and selection of hydrologic modeling systems for climate change projections is a critical, but often underappreciated step. When making a long-term climate projection, verification is impossible. As such it is important to be sure that model deficiencies are addressed at the physical processes level, not just calibrated away, and that a range of modeling decisions are analyzed to quantify uncertainty in the modeling process. Dr. Gutmann will present work analyzing physical process representation in models, the impact of model selection on climate projections, and a flexible hydrologic modeling system capable of representing our uncertainty in physical process representation.

Dr. Connie Woodhouse, Professor

School of Geography and Development
University of Arizona
conniew1@email.arizona.edu

Research Interests: Climatology, paleoclimatology and water resources.

Evaluating the influence of air temperature and soil moisture conditions on Colorado River streamflow.

ABSTRACT: Upper Colorado River flow is largely influenced by winter precipitation, with runoff season temperature and antecedent fall soil moisture playing relatively minor roles. However, in some years, runoff season temperature is more influential, explaining a greater portion of the variance in annual streamflow. These types of years appear to be occurring with greater frequency since the 1980s. Temperatures also influence the impacts of drought, and have both moderated and exacerbated the impacts of precipitation deficits on streamflow. Paleoclimatic data suggest the influence of warm temperature on streamflow and drought may be greater now than over the past five centuries.

Dr. Stephanie McAfee, Assistant Professor

Department of Geography, University of Nevada, Reno
smcafee@unr.edu

Developing synthetic streamflow time series using precipitation, temperature and soil moisture.

Dr. Flavio Lehner, Postdoctoral Fellow

National Center for Atmospheric Research,
Research Applications Laboratory
flehner@ucar.edu

Research Interests: Hydrology, climate variability and change, statistical forecasting.

The influence of temperature on runoff efficiency - implications for streamflow forecasting.

ABSTRACT*:* Dr. Lehner will discuss recent hydroclimate changes in the Upper Rio Grande basin with a focus on streamflow and runoff ratio, as well as research that quantifies how exceptional these recent changes are in context of the last several hundred years. He will further illustrate how variations in temperature are playing an important role in shaping years of very low runoff ratio. Based on these results, he will show first examples of successful skill improvements in seasonal streamflow forecasting by including seasonal temperature forecasts for a number of gages in the Upper Rio Grande and Upper Colorado River.

Mark Spears, Hydraulic Engineer

U.S. Bureau of Reclamation

jspears@usbr.gov

Research Interests: Crops and riparian evapotranspiration and surface water evaporation.

Estimating irrigation demands and reservoir evaporation demands for climate change risk assessment.

ABSTRACT: Mr. Spears will present estimates of future agricultural water demands and reservoir evaporation contained in the recent "West-Wide Climate Risk Assessments: Irrigation Demand and Reservoir Evaporation Projections" and "Colorado River Basin Study" reports. He will also discuss methods, including the use of climate projections for temperature and precipitation to estimate future irrigation demands in eight major western U.S. river basins and evaporation on 12 Reclamation reservoirs. His presentation will also address differences in the methods used for the two studies.

Dr. Kathleen Holman, Meteorologist

U.S. Bureau of Reclamation (former position)

Research Interests: Open-water evaporation, large-scale climate variability, snow observations and modeling, and sources of uncertainty in streamflow forecasts.

Estimating reservoir evaporation - current practice and state-of-the art.

ABSTRACT: Evaporation is a process that influences the water and energy budgets of lakes and reservoirs. In this talk, Dr. Holman will discuss common methods used to estimate evaporation within the operational and research communities. Common methods used to estimate evaporation include pans, bulk mass transfer equations, water budgets, energy budgets, eddy covariance techniques, and combined approaches. Each method is characterized by a unique set of strengths and weaknesses, which need to be carefully evaluated when selecting a method for application. She also will discuss future needs related to measuring and understanding reservoir evaporation in the western U.S.

Appendix 3. Symposium Presentation Material

Large file: Contact Keely Brooks at 702-822-3349 for symposium presentation material.