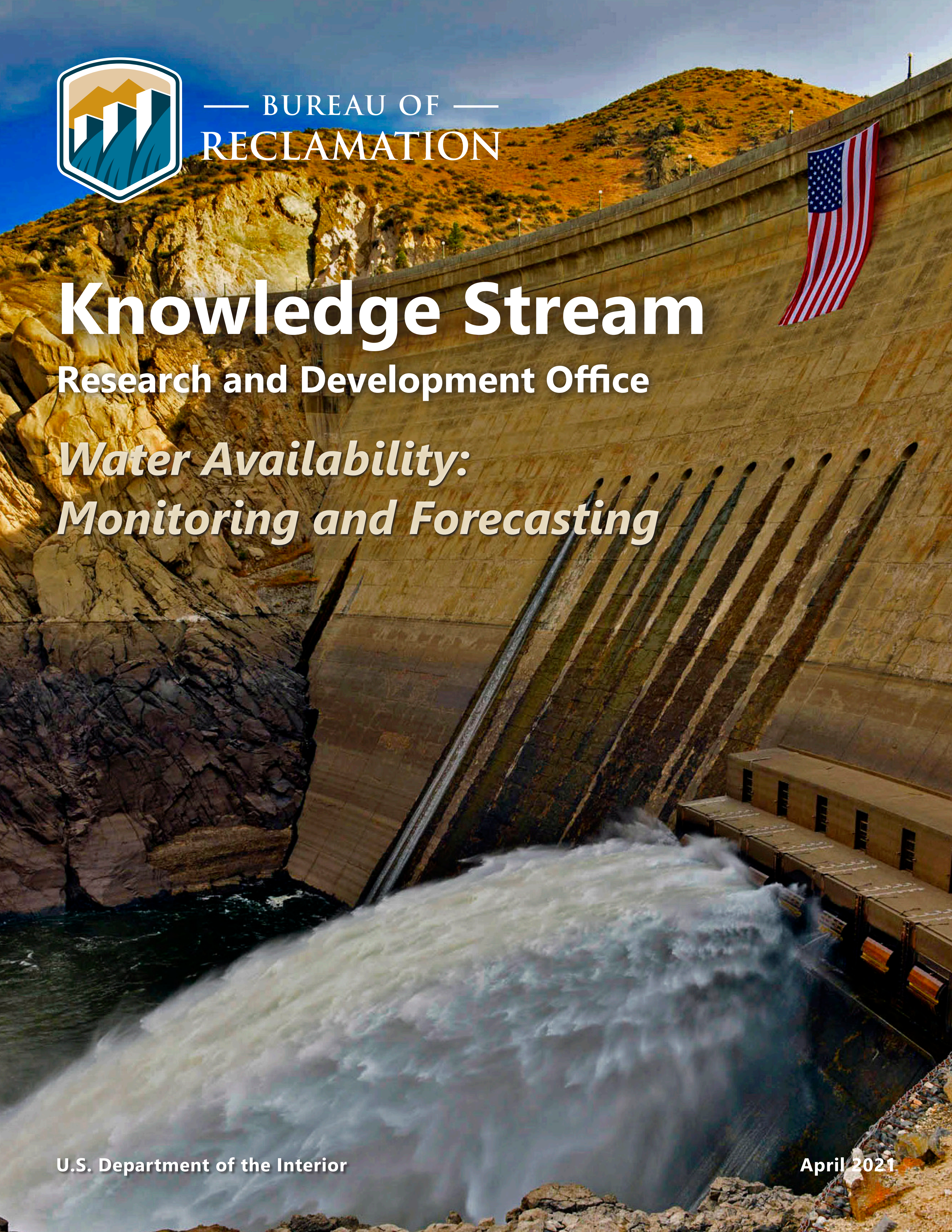
BUREAU OF RECLAMATION

Knowledge Stream

Research and Development Office

Water Availability: Monitoring and Forecasting



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Message from R&D

Welcome to the Spring 2021 issue of the *Knowledge Stream*. In this issue, we highlight research related to forecasting water availability. For many Reclamation Projects, springtime means rivers swollen with snowmelt. Reservoir operators must manage this inflow, balancing the need to maintain empty space for flood risk reduction with the need to capture inflow to build water supply for warm season deliveries and uses. Confounding this balancing act are the challenges of water demand changes, climate variations from floods to droughts, and long-term climate change. To address this challenge, operators rely heavily on forecasts of water availability–from sub-daily streamflow forecasts to seasonal water supply forecasts. Further, advances in monitoring and forecasting provide operators the opportunity to introduce new, more effective ways to conduct reservoir operations.

In this issue, we are excited to feature water availability monitoring, forecasting, and long-term projection activities being carried out by Reclamation scientists, engineers and partners, ranging from research to applications. You'll read about:

- Efforts related to basin condition monitoring, specifically snowpack, and the use of this information in streamflow forecasting.
- Efforts to improve seasonal water supply forecasts and tools used by operations groups.
- Reclamation's 2021 SECURE Water Act Report to Congress on long-term water projections.
- An evaluation of NOAA's National Water Model for Reclamation applications.
- Research on risk-based reservoir operations that better leverage ensemble forecasts.

As always, we appreciate you reading about innovation funded by Reclamation's R&D programs. Please enjoy this issue of the Knowledge Stream and offer us any feedback for improving our strategies to transfer solutions to users.

About the *Knowledge Stream*

The *Knowledge Stream*, published by the Bureau of Reclamation's Research and Development Office, is a quarterly magazine bringing mission-critical news about the agency's innovations in the following:

- Science and Technology Program
- Desalination and Water Research Purification Program
- Prize Competitions
- Technology Transfer
- Open Water Data...and more.

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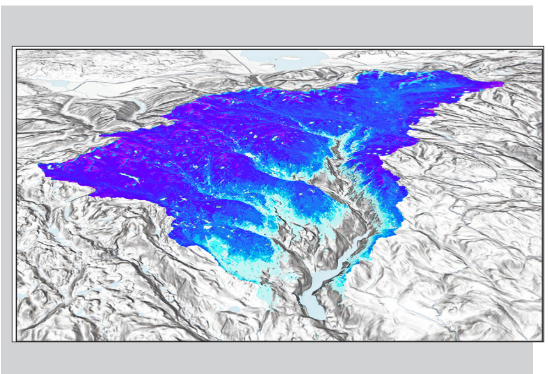
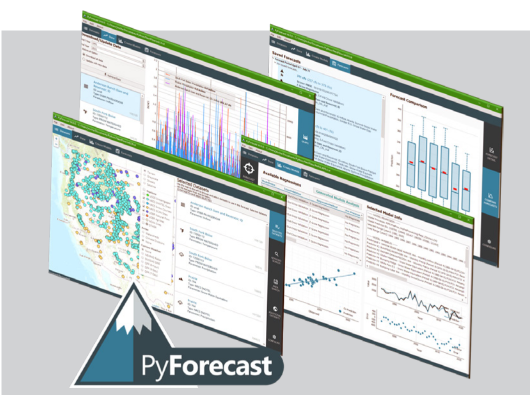


Snow Monitoring & Water Supply Forecasting: **pg. 11**



PyForcast: **pg. 17**

Front Cover: Water release at Arrowrock Dam, Idaho.
Back Cover: Anderson Ranch Dam and Powerplant, Idaho, in winter.

Community Needs

Hitting to All Regions: Perspectives on Forecasts

By Ken Nowak
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Reclamation manages over 300 reservoirs within the 17-western state domain, across diverse hydroclimates that range from high mountain, to coastal, to desert, to plains. Some are influenced by the North American monsoon, others are dominated by atmospheric rivers, and many are impacted by a spring freshet. Projects also range in size–from thousands of acre-ft to millions of acre-ft of storage and in authorized propose–flood control, hydropower, water supply, recreation, and others. Operations and forecast use are commensurately varied. The perspectives that follow shed light on forecast use and needs across Reclamation.

Name: Peter Cooper,
CPN Region Water Management Group

Scope: The CPN Region mainly consists of the Columbia River mainstem and its tributaries, covering the states of Idaho, Washington, Oregon, and portions of Wyoming, Montana, Nevada. The reservoirs we manage are located in basins that cover the full range of primarily rain driven to primarily snow driven systems.

Forecasts used: Internally, CPN Region uses Multiple Linear Regression (MLR) and Principal Component Regression (PCR) to produce statistical runoff forecasts on a monthly basis (January through June) for 34 locations. We also consider and use forecasting products produced by external agencies, including the Northwest River Forecast Center, NRCS, and Corps of Engineers. Basin condition monitoring is an integral part of the CPN forecasting procedure, and includes analyzing streamflow, reservoir, weather, snow, precipitation, soil moisture, and other conditions from many different data sources.

Room for improvement: Improvement in the skill of future weather conditions (precipitation and temperature) would provide benefits to improving the skill of our runoff forecasts. Even with the peak snowpack known in April, large variability in the forecasted versus actual runoff can still occur based on subsequent spring weather conditions. Another area that we think will provide improvement is incorporating gridded data, such as precipitation, snow water equivalent, and soil moisture, into our suite of forecasting products.

Of note: Runoff forecasting and basin condition monitoring go hand in hand in the CPN Region. We devote a lot of time analyzing basin conditions in coordination with running our forecast programs to ensure the results are reasonable and to understand the range of possibilities.

Name: Mike Follum,
Wyoming Area Office (WYAO)

Scope: WYAO manages reservoirs along the North Platte river system in Wyoming and Western Nebraska, and reservoirs along the Wind/Bighorn and Shoshone river systems in Western/Northwestern Wyoming.

Forecasts used: Linear Regression Algorithms and PyForecast. The linear regressions algorithms use snowpack, precipitation, and streamflow as their drivers. They have a longer track record and are trusted within the Area Office. PyForecast has the ability to use more input data and produce ensembles, which has a lot of promise. With more testing and development, I think PyForecast will become our main forecast method in the next few years.

Room for improvement: Our basins are very diverse and cover large spatial areas. I think accounting for spatial differences (flat vs. steep; wooded vs desert; etc.) within PyForecast could be helpful. One way to accomplish this is having multiple instances of PyForecast that talk together. Another method is to use a form of "clustering" within the same PyForecast run.

Of note: If done correctly, I do also think incorporating components of the Forecast Informed Reservoir Operations (FIRO) concept could help operations as a whole.

Name: Alex Pivarnik,
Boulder Canyon Operations Office

Scope: Colorado River Basin mid-term operations and planning, short-term scheduling, and real-time control of facilities. Each of these require RiverWare modeling on different time scales, from 5 years down to hourly unit scheduling at a single project.

Forecasts used: Colorado Basin River Forecast Center's (CBRFC) Water Supply Forecast for use in the 24 Month Study, as well as the CBRFC's Ensemble Streamflow Prediction Traces for use in the Mid-Term Probabilistic Operations Model.

Room for improvement: A forecast which can help predict Lower Colorado River Basin monsoonal weather patterns.

Of note: In partnership with Albuquerque Area Office and the National Center for Atmospheric Research, Lower Colorado Operations is working on addressing the issue above through a monsoonal weather typing project for Arizona and New Mexico. This builds on the work of S&T 1782.

Name: Chad Moore,
San Joaquin River Restoration Program

Scope: The Restoration Program partners with Reclamation's South-Central California Area Office in forecasting inflows to Millerton Lake (Friant Dam)

Forecasts used: This Joint Forecasting Team uses the NWS River Forecast Center products and California Department of Water Resources runoff forecasts as the primarily pillars of information, and we supplement these with Airborne Snow Observatory measurements, snowpack models such as iSnobal, historic analogs, and some experimental models that we built in-house. We developed a process which allows us to synthesize the various data streams to produce a hybrid forecast, which then becomes the basis for reservoir operations.

Room for improvement: As we have access to better tools to measure or predict the snowpack volume, we recognize how little we understand about runoff efficiency. With the extreme inter-annual variability in precipitation in the Sierra Nevada, it appears that understanding soil moisture deficits and vegetation change is as important as understanding snowpack water volume.

Of note: The San Joaquin River is the southernmost range extent for Spring-run Chinook Salmon, yet climate models predict that because of the high elevation terrain, snowpack will persist in our basin while more northerly basins become rain-dominated over time.

Name: Susan Behery,
Western Colorado Area Office

Scope: San Juan River Basin, CRSP Initial Unit Navajo Dam (and five other smaller federal projects)

Forecasts used: CBRFC primarily, NRCS secondarily

Room for improvement: The 10-day to 1-month forecast is lacking and is essential for spring operations. This is the most important decision-making window for operations in my basin and the lack of skill in that timeframe significantly increases the risk of missing ESA targets. Additionally, dust impacts is not currently accounted for in a very robust way in any forecasting model.

Of note: San Juan River Basin operations are planned through probabilistic modeling using Riverware. I utilize all 35 CBRFC traces for regular operations planning. I also heavily rely on dust-on-snow measurements as runoff in the San Juan mountains is heavily impacted by dust. CBRFC forecasts are not able to ingest dust as an input into their energy balance model at the moment, but it is used to correct the forecast during melt season. As a compliment, I have developed a qualitative way of assessing impacts and making use of dust information in forecasting.

Key Perspectives

On the Evolution of Forecasts and Forecast Use in Water Management

By Ken Nowak
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There is a long history of forecast use in western water management. For much of the Reclamation domain, snow plays a notable role in water supply and thus, its characterization is the foundation upon which many forecasts are based. Snow surveys in the Sierra date back to early 1900s. These surveys informed early forecasts, such as those pioneered by James Church at the University of Nevada Reno regarding the anticipated rise in Lake Tahoe from snowmelt. This information informed dam releases and helped to ease local tensions over lake levels. Owing to the success and value of these early efforts, in 1935, Congress formed the Federal-State Cooperative Snow Survey, now known as the Snow Survey and Water Supply Forecasting Program of USDA's Natural Resources Conservation Service.

Today, snow and other basin condition monitoring is enhanced in spatial coverage and technology precision. These and other advancements have enabled a host of forecast products that span short term streamflow to seasonal water supply forecasts and are relied on by water managers across the West. However, water management and forecasting in many ways have made an implicit (or explicit) assumption of a stable or 'stationary' hydroclimate. Such assumptions include when peak snow accumulation will occur or that the weather and hydrology of decades past is equally relevant as compared with more recent observations. These have implications for forecast performance and water management protocols such as how and when reservoirs fill.

Looking forward, growing demand for water, coupled with the dynamic of a changing climate will only increase the importance and prevalence of forecasts in water management. However, the extent to which forecasts will mitigate impacts of climate change is likely to be a function of how the forecasts themselves can adapt and perform as conditions change. As a corollary, there will be opportunities for water managers to seek operational practices and frameworks that are flexible to take advantage of the likely evolving and improving nature of forecasts.

Reclamation's 2021 SECURE Water Act Report

Climate Change Poses a Significant Challenge to the Security and Use of Water Resources

By Avra Morgan
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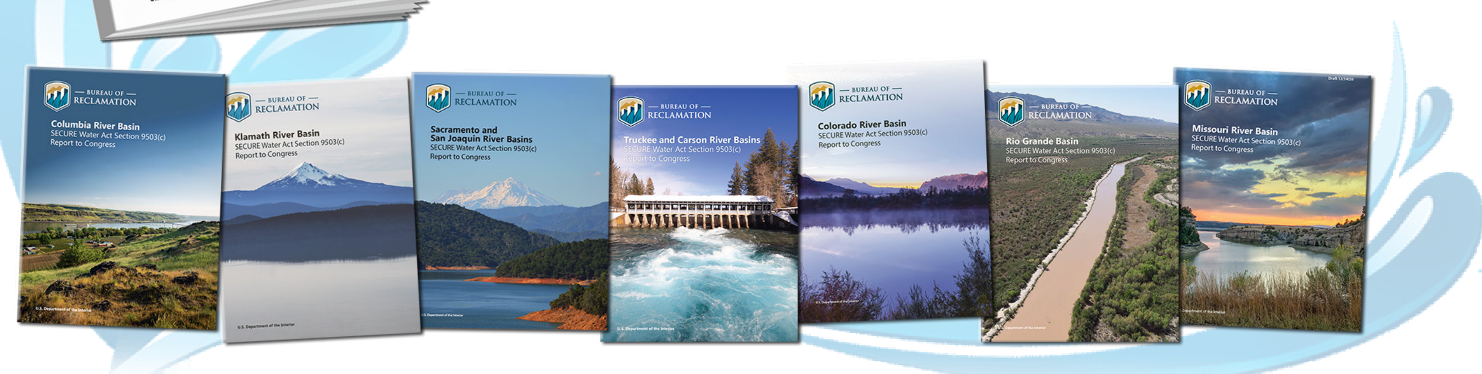
To carry out our mission, Reclamation relies on observations and future projections of water supply and demand, based on information about temperature, precipitation, snowpack, streamflow, water demands, and groundwater. These conditions, which contain inherent uncertainties due to climate variability, are influenced by climate change – increasing the uncertainties in our planning and operations. Understanding how changing conditions impact water management helps us to make informed decisions and to develop innovative approaches to meet these challenges.

In accordance with the SECURE Water Act (Public Law 111-11, Subtitle F of Title IX), Reclamation submits a report to Congress every 5 years. This Water Reliability in the West - 2021 SECURE Water Act Report (2021 Report), submitted to Congress on January 15, 2021, provides a West-wide assessment of expected changes to water supplies, uses, and demands—and describes collaborative actions taken to increase water supply reliability since the 2016 SECURE Water Act Report. The 2021 Report summarizes more detailed information from the West-Wide Climate and Hydrology Assessment (2021 West-Wide Assessment), and the Basin Reports, which include more in-depth information for each of the eight major Reclamation river basins identified in the SECURE Water Act.

All SECURE Water Act Reports are available at https://www.usbr.gov/climate/secure. The website also features an online tool that pulls this information together in an easy-to-use format with interactive explanations and additional examples of how Reclamation is increasing the reliability of water and power deliveries.

Reclamation's 2021 West-Wide Assessment discusses potential impacts from climate change to water supply and demand across the West. It also includes an analysis of paleohydrology, which focuses on droughts of the distant past and how such droughts may change in the future.



The 2021 West-Wide Assessment presents hydroclimate and paleohydrology information developed across the eight major Reclamation river basins, including:

- Downscaled hydroclimate projections West-wide and by basin
- The Palmer Drought Severity Index (PDSI) – which relies on soil moisture to measure drought – was used to evaluate drought severity, duration and frequency dating back as far as 1473 using paleohydrology, and projecting out into the future to 2099
- Streamflows based on tree-ring reconstructions at 152 sites across the West, which are evaluated over a common time period of 1685 to 1977 and used to understand wet and dry conditions centuries before stream gages were installed. These were used to:
  - ◊ Demonstrate how this information may be used along with gaged streamflows to develop a data-based understanding of drought risk
  - ◊ Demonstrate, by running reconstructed streamflows through system operations models, to see how current operations would perform if drought scenarios from the distant past were to occur today
- An analysis of risks to urban water demands showing that irrigation demand for turfgrass will substantially increase due to evapotranspiration and net irrigation water requirements
- Climate change impacts to groundwater through a synthesis of groundwater projects, including collaboration with the U.S. Geological Survey (USGS) on impacts within the Colorado River Basin

The 2021 West-Wide Assessment relies on the best available information and well-vetted methods, using approaches documented in peer-reviewed literature. However, uncertainties still exist and are discussed, including those associated with climate projections and assessing hydrologic impacts. This work is peformed by Reclamation's Technical Service Center in partnership with USGS, University of Arizona, Columbia University, Desert Research Institute, National Center for Atmospheric Research, Aspen Global Change Institute, and in collaboration with Reclamation Regions and Area Offices.

BASIN MONITORING

Snow Water Supply Forecasting Program

Legislation Brief: HR 133 Section 1111

By Ken Nowak & Avra Morgan
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Section 1111 of HR 133 (Consolidated Appropriations Act, 2021) establishes a Snow Water Supply Forecasting Program at the Department of the Interior. Reclamation, acting on behalf of the Secretary, will implement this program. Per the Act, a report to Congress on snow measurement technologies will be delivered by October 1, 2021. The report will summarize the use of emerging technologies to improve snowpack measurement, the benefits of those technologies on the environment and water supply reliability, and partners' criteria for operationalizing these technologies. Informed by the report to Congress, Reclamation will coordinate with Federal partners to support implementation of technologies that improve snow measurement and subsequently, water supply forecasting. Development of the report to Congress is being led by the Science Advisor Organization with a team including membership from each of Reclamation's regions.

Snow Monitoring and Water Supply Forecasting

Assessing the Impact of High-Resolution Airborne Snow Data on Water Supply Forecast Skill

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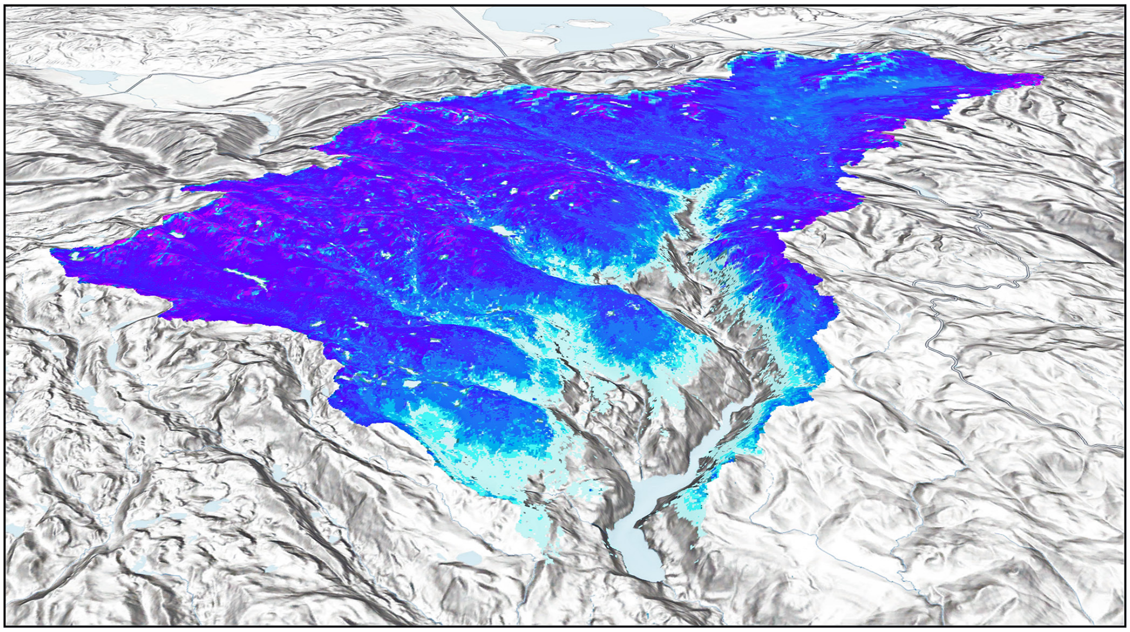

Airborne Snow Observatory's 50m snow water equivalent dataset for the Tuolumne Basin for April 1, 2017.

Measuring mountain snowpack is central to seasonal streamflow forecasting in the Western United States. Advances in airborne remote sensing have expanded observational capacity with greater resolution and coverage across mountain landscapes. Such advances have outpaced our ability to use the new high-resolution data in streamflow forecasting. Over the last decade, the Airborne Snow Observatory (ASO) has developed a methodology to generate maps of snow water equivalent (SWE, or the amount of water held in snow) and albedo from a combination of snow depth from lidar/spectrometer flights and observation-informed snow density modeling. ASO has flown over 60 flights of the Tuolumne Basin in the California Sierra Nevada. This record now includes some of the Sierra's lowest and highest snowpack years, creating an opportunity to evaluate best practices for using high-resolution SWE information in water supply forecasting.

Reclamation partnered with NCAR and ASO to explore these opportunities using the existing ASO datasets. This project evaluates how traditional snow pillow station-based estimates of basin-wide SWE compare to more spatially complete estimates from ASO, and the impact these differences have on streamflow modeling and forecasts. The tradeoff for increased spatial coverage is the loss of temporal coverage, a feature of the stations. Assessing the relationship between stations, which monitor continuously, and ASO flights, which capture a snapshot in time, this project identified that approximately 5-10 ASO flights, combined with stations, are sufficient to define 95% of the variability in the remaining flights. However, this relationship starts to break down for times with very high or low SWE conditions, indicating that more flights are needed to improve the estimation of that relationship. Next steps will benchmark the impacts of incorporating ASO information into forecasts, with an interest in developing guidance on when ASO flights can provide the most information for predictions, and how best to assimilate that information into forecast models.

Low Elevation Snow

Assessing the Influence of Model Configuration on Low Elevation Snowmelt Runoff Flooding

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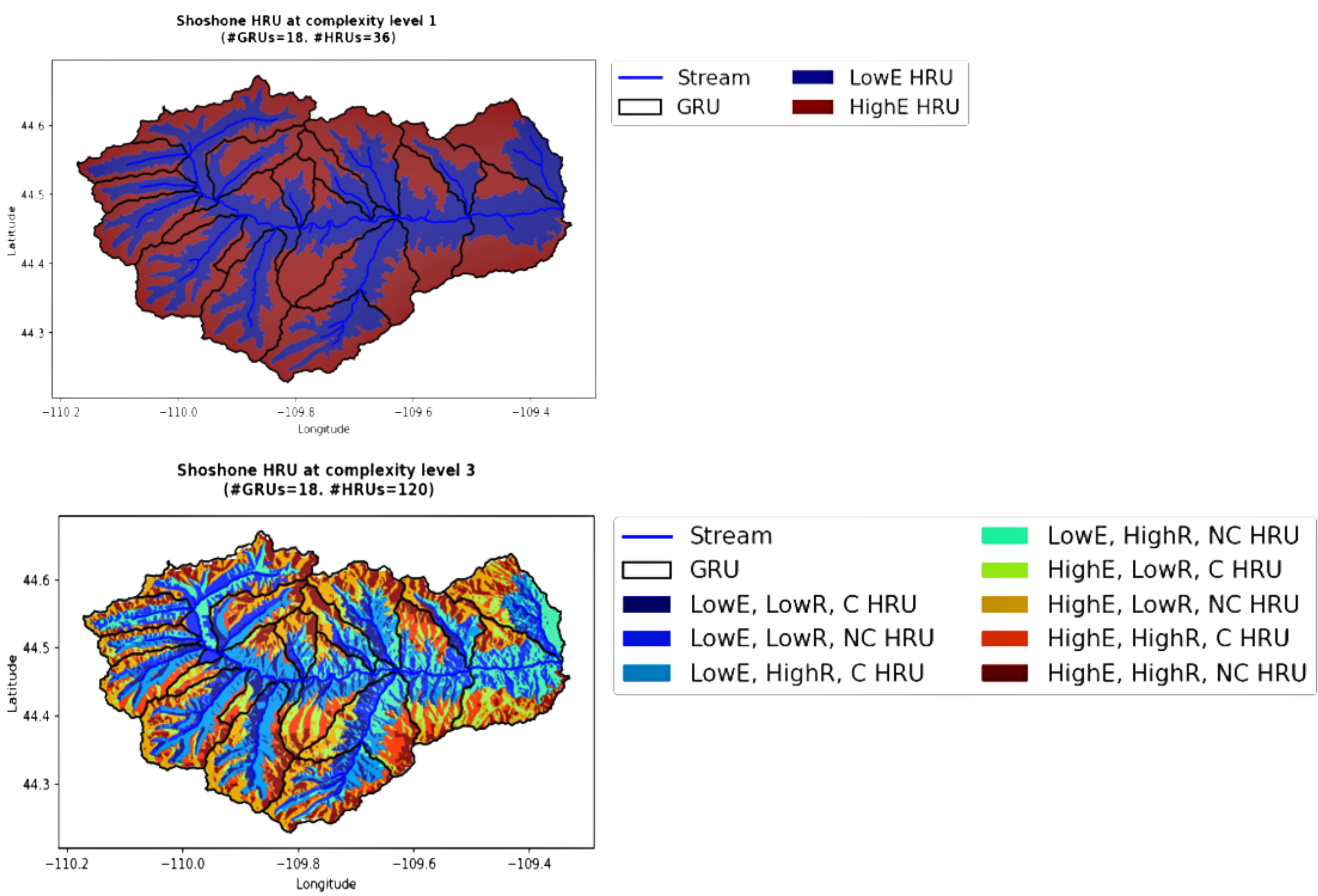
S&T Project page: www.usbr.gov/research/projects/detail.cfm?id=19178

The Bighorn River basin upstream of Bighorn Lake is predominantly high elevation desert and plains, with the headwaters extending into the Bighorn and Wind River Mountains and the Gros Ventre Range. Reclamation operates several reservoirs within this basin including Boysen Reservoir, Buffalo Bill Reservoir, and Bighorn Lake. Water management is challenged by large uncertainty and errors in both seasonal water supply forecasts and short to medium range (0-10 day) forecasts. One hypothesis to explain forecast errors is that current streamflow forecast models do not accurately represent the snowpack and snowmelt events, particularly in plains.

To test this hypothesis, this project pursued three distinct tasks. First, snow data products beyond SNOTEL were investigated for their potential to provide better understanding of snow extent across the basin. Products included NOAA's SNODAS gridded fractional snow-covered area (fSCA) and snow-water equivalent (SWE), NASA JPL's MODSCAG fSCA product and NASA's Normalized Difference Snow Index, both of which are derived from MODIS satellite observations. Second, a Python tool called the Snow-Hydrology Repo for Evaluation, Analysis, and Decision-making (SHREAD) was developed to easily retrieve, format, and consistently output snow data products (such as timeseries of fSCA and SWE across a river basin) to improve their accessibility for water management uses. These first two tasks provided access to snow datasets that could be used to monitor and analyze snow across the basin, as well as supporting a third task, hydrologic modeling and validation.

The third task is applying the SUMMA hydrology model in the Shoshone River basin (a part of the Bighorn River basin) to investigate whether the spatial discretization of a hydrologic model can influence its ability to represent simulated snow variables, impacting in turn the model's ability to simulate and forecast runoff. Physical basin attributes – specifically elevation, vegetation, and solar loading (how much sun or solar radiation is received) – are known to control snow accumulation and melt. Breaking up the hydrology model resolution to resolve these attributes could allow for a better representation of the snowpack.

The baseline model considered used lumped USGS HUC12 catchments or subbasins as a 'grouped response unit' (GRU) with the GRU's mean elevation and most common vegetation type. More discretized models then broke up each grouped response unit (GRU) into smaller hydrologic response units (HRU). The simplest of these used only elevation to split each subbasin (similar to the NWS hydrology models), with one HRU representing lower-elevation, and the other representing higher elevation areas. The most complex broke up each GRU into HRUs by elevation, by solar loading (high and low) and by vegetation type (assigning two types, one with canopy and one without). Model forcings were similarly discretized. The development of the varying-complexity hydrology models is complete and the results are currently being examined. The evaluation will determine whether model representations that include more resolution in simulating subbasin conditions that impact snow simulation offers the best skill both in simulating streamflow, validating against snow data available from SHREAD. We anticipate that the project overall will provide insight into the nature of runoff prediction errors in the Bighorn River basin and more generally into the suitability of different modeling approaches for forecasting and climate sensitivity experiments. The discretization tool and SHREAD software will also be publicly accessible outcomes from the project.



SUMMA model of the North Fork Shoshone River, WY, using different levels of complexity to define subbasin hydrologic response units (HRUs). The HRU discretizations are based on elevation (lowE/highE), canopy-cover (C/NC), and solar radiation (lowR/HighR). Black lines define the subbasins (GRUs), with the shading showing the different HRUs.

WATER FORECASTING

Southwestern Water Supply Forecasting

Improving the Resiliency of Southwestern U.S. Water Supply Forecasting in the Face of Climate Trends and Variability

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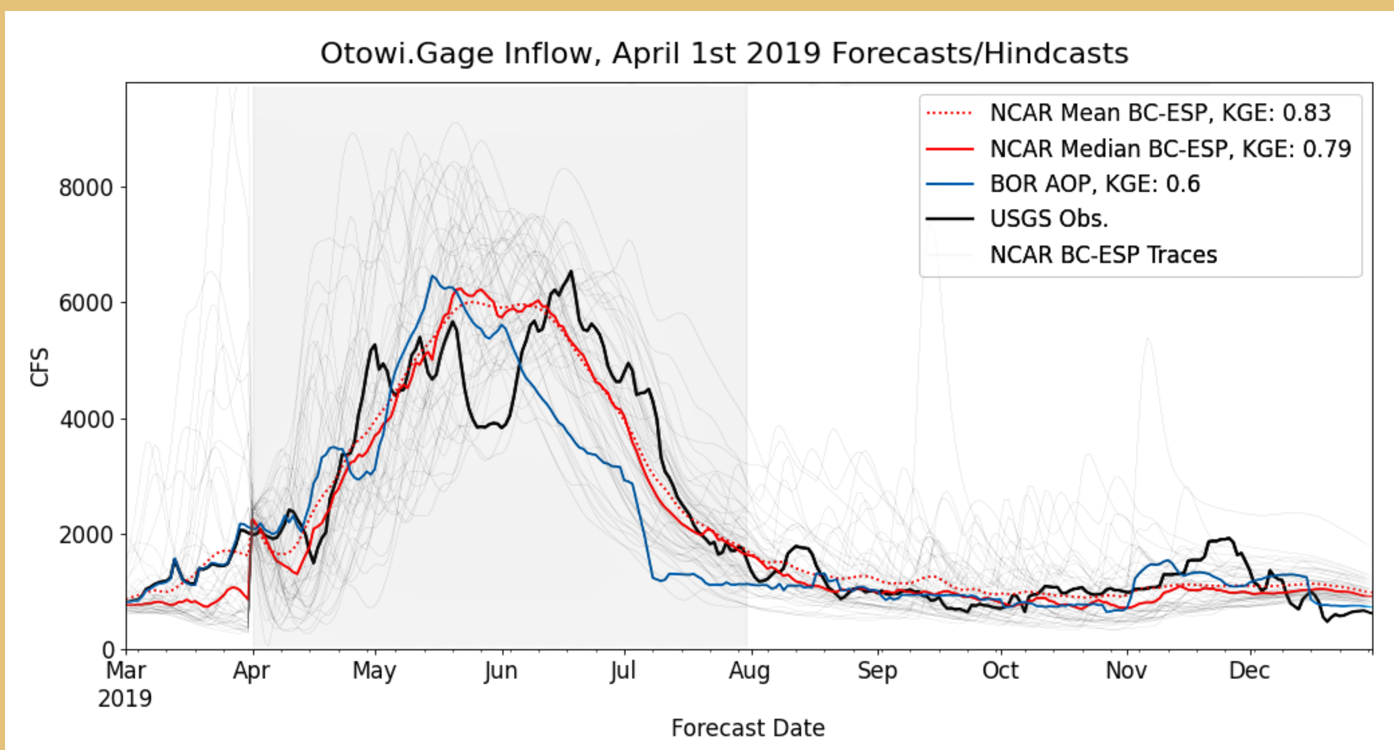
Recent warming in the southwestern United States has been associated with decreasing runoff efficiency and lower-than-expected spring runoff volumes. This trend is especially important in years such as this (2021). More than 80 percent of New Mexico is currently experiencing extreme or exceptional drought (U.S. Drought Monitor, March 2021), and irrigation districts have made announcements of shortened irrigation seasons. The combined effect of warming on snow accumulation and soil moisture are reducing runoff efficiency. This may systematically reduce the skill of conventional seasonal water supply forecasts (Lehner et al., 2017) like Natural Resources Conservation Service's Rio Grande Basin Outlooks, which are trained or calibrated to historical relationships between runoff and hydroclimate variables.

Forecasts of spring snowmelt runoff volume and timing provide critical information to support key water management decisions in the Upper Rio Grande (URG) each year. Concerns about decreases in the skill of traditional forecasts have motivated research efforts to enhance the robustness of streamflow forecasting techniques in the face of hydrologic non-stationarity. A team of researchers from the National Center for Atmospheric Research (NCAR) and partners from Reclamation's Albuquerque Area Office set out to accomplish the following goals: enhance the resiliency of streamflow forecasting to trends and variability, understand the underlying hydroclimate dynamics, and assess both the broader west-wide extent of potential changes in hydroclimate predictability and the potential skill of current climate predictions.

Early efforts of this project have focused on the development of calibrated NCAR watershed modeling using the Structure for Unifying Multiple Modeling Alternatives (SUMMA) model (Clark et al., 2015) as a testbed for evaluating prototype strategies for streamflow forecast improvement using Ensemble Streamflow Prediction (ESP). Under the framework, NCAR researchers generated a 50-year sequence of ensemble streamflow hindcasts for key water management locations in the URG basin. From this baseline, efforts are currently underway to develop trend-aware forecasts that use historical analyses to correct for systematic biases and leverage new climate information such as temperature forecasts from the National Multi-Model Ensemble (NMME). The resulting best-performing strategies for runoff volume and timing prediction for annual operations planning (see figure on next page) could be adopted by Reclamation for use with new and developing ESP forecasts from the National Weather Service River Forecasting Centers.

A second project objective is to identify changing hydrologic predictability throughout the Reclamation domain. Using the SUMMA model, a retrospective analysis will identify watersheds where climate trends and variability are systematically and significantly altering the predictability of spring runoff. Additional climate information from the NMME or other sources could ultimately be used to enhance water-supply forecasts for trend-sensitive locations.

Implementation of trend-aware and process-based strategies that combine information from historical reforecasts as well as new climate information into current operational practices offers significant promise for developing more climate-resilient water supply forecasting systems in the URG and throughout Reclamation's service area.



Comparison of April 1 2019 prediction of seasonal hydrograph shape and volume at the Rio Grande at Otowi Bridge, New Mexico gage (USGS 08313000) by several methods, including bias-corrected NCAR ESP and Reclamation analog trace selection (labeled 'AOP'), compared to USGS observations. The performance of each approach in terms of the Kling Gupta Efficiency (KGE; higher scores are better) is noted in the legend.

Streamflow Forecast Rodeo

Harnessing Advances in Data Science to Improve Streamflow Forecasting

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Streamflow Forecast Rodeo: www.usbr.gov/research/challenges/streamflowrodeo.html

Streamflow forecasting is integral to water management. With higher skill forecasts, water managers are better equipped to operate facilities for high flows, mitigate impacts of drought, and meet operating objectives such as improving water supply reliability and increasing hydropower generation.

Recent advances in data science methods such as Artificial Intelligence (AI) / Machine Learning (ML), along with continued advances in High-Performance Computing (HPC), provide new opportunities to improve streamflow forecasting. In particular, AI/ML methods have the potential to improve on traditional physically-based streamflow forecast methods via hybrid or purely data-driven approaches. To this end, Reclamation partnered with the Centre for Energy Advancement through Technological Innovation's Hydropower Operations and Planning Interest Group (CEATI-HOPIG), NASA Tournament Lab, and Topcoder to design and launch a prize competition to spur innovation in the field of streamflow forecasting, with emphasis on assessing the potential application of ML/AI for streamflow forecasting.

The research community has begun to explore the use of AI/ML methods in streamflow forecasting. However, while several studies demonstrate that these methods can produce reasonably accurate forecasts in case studies across a range of climate and hydrologic conditions, few studies have directly compared the performance of streamflow forecasts based on AI/ML methods to those of traditional forecast system.

The Streamflow Forecast Rodeo seeks to improve the skill of short-term streamflow forecasts (10 days) through a year-long prize competition paired with a similar year-long evaluation of existing forecast technologies.

The prize competition focuses on 10 locations within the Reclamation domain; the technology evaluation includes 9 additional locations across North America "sponsored" by project partners (TVA, DOE, Hydro-Quebec, and the Southern Company).

The prize competition includes two phases – a "warm-up" competition where solvers develop their forecast systems based on hindcasting historical conditions and a "real-time" competition where solvers use their forecast systems to provide real-time daily streamflow forecasts. The warm-up competition was completed in September 2020; the real-time competition was launched September 23, 2020 and will continue through September 2021. The prize competition offers up to $500,000 in cash prizes across the two phases.

The real-time competition requires solvers to develop and implement streamflow forecast systems for selected locations across the western United States. Solvers' forecast systems are executed on a daily basis and the skill of each resulting streamflow forecast is evaluated against observed streamflow. Cash prizes are awarded based on forecast performance (skill) over monthly, quarterly, and year-long award periods. The 15 systems exhibiting the highest skill are eligible for cash prizes. To receive a cash prize, however, a solver's forecast system must also exhibit higher skill than benchmark, state-of-practice operational forecasts from the technology evaluation portion of the project.

Since launching in September 2020, the real-time competition has averaged approximately 50 participants each month. At least 10 participants have outperformed the benchmark, state of practice forecast each month.

PyForecast

PyForecast - Runoff Forecasting for Reservoir Operations

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PyForecast GitHub Repository: https://github.com/usbr/PyForecast

Forecasts are useful pieces of information that drive our everyday lives. The weather forecast will tell you whether you need to bring a coat or wear shorts and your electric companies energy-use forecast might help you budget for this month's electric bill. For Reclamation water managers, the runoff forecast serves the same purpose. The runoff forecast helps operators develop a plan for managing our reservoirs. High runoff forecasts help operators determine the amount of reservoir space they would need to conserve to control potential flood flows. Moderate and low runoff forecasts force operators to plan their reservoir releases to fill the reservoir. In all cases, having a reliable and defensible forecast is crucial for communicating our decision to stakeholders and the public.

Reclamation water managers have considered forecasts generated by the various River Forecast Centers (RFC) and the Natural Resource Conservation Service (NRCS) for as long as these agencies have been generating forecasts. Reclamation water managers in the MB and C-PN regions even make their own forecasts using locally developed legacy processes. These processes range in complexity and scope, from single spreadsheet calculations to 1,000-line FORTRAN programs developed before the era of modern PCs. A need for modernization and standardization was identified in both the C-PN and MB regions, and Reclamation's Science and Technology Program provided the perfect opportunity to pursue a new, unified direction in water supply forecasting.

MB region water managers were already using an early version of PyForecast which was developed in-house. Development of the software began in 2018 with initial goals of gathering a multitude of hydrologic datasets in one location, and producing fast, robust forecasts. Since 2018 development has moved in the direction of user-friendly user interfaces, data and science driven forecast processes, and increased compatibility with ever-changing data services, forecast formats, and statistical methodologies. MB has been able to leverage a solid base of testers in the region to help with debugging and feature recommendations. C-PN water managers saw the utility of PyForecast and collaborated on further development of the software in collaboration with MB and TSC software developers.

The resulting product from this collaboration has already proven to be more modular, user-friendly, modern, and feature-rich in terms of building and training forecast models and in issuing real-time runoff forecasts. C-PN is currently evaluating and running PyForecast in parallel with our existing forecasting methods. Forecasts generated by PyForecast are currently on par with our other generated forecasts and with those generated by the RFC and NRCS. Hindcast comparisons for a few test basins in C-PN have also been promising with significant improvements in the error statistics as we compare PyForecast hindcasts with historical forecasts.

PyForecast is already in use in MB region as their primary tool for runoff forecasting with C-PN also trending in this direction. It is an exciting time for runoff forecasting as we explore the addition of more datasets, mathematical algorithms, and machine learning techniques to produce more skillful runoff forecasts. More skillful runoff forecasts better positions us as an agency to fulfill our mission of managing water in the hydrometeorologically diverse west.

Structure for Understanding Multiple Modeling Alternatives (SUMMA)

A New Hydrometeorological Modeling Resource for Watershed Research and Applications in the Western United States

By Andy Wood, with Project Partners; USACE, University of Washington, & Reclamation
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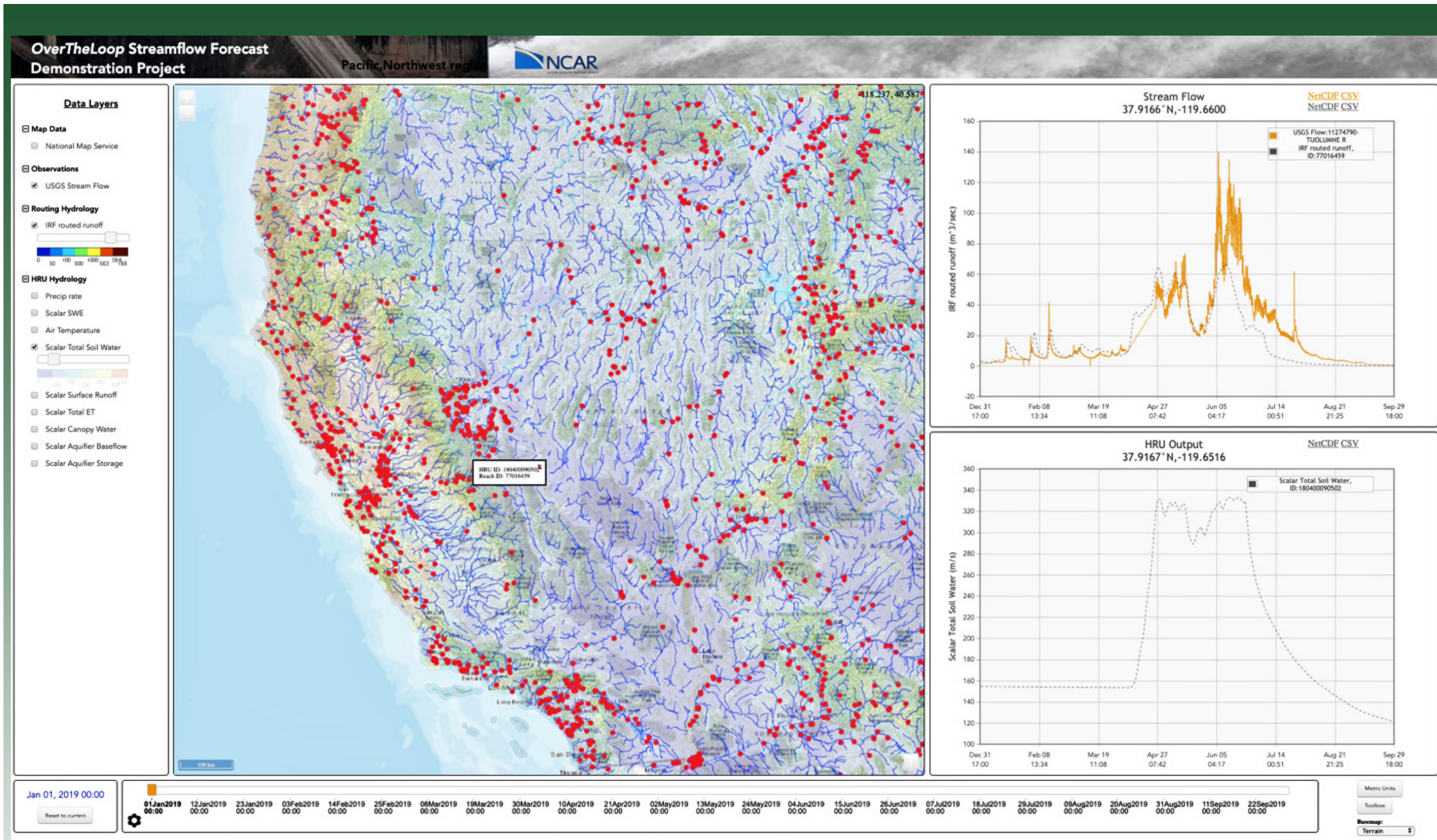
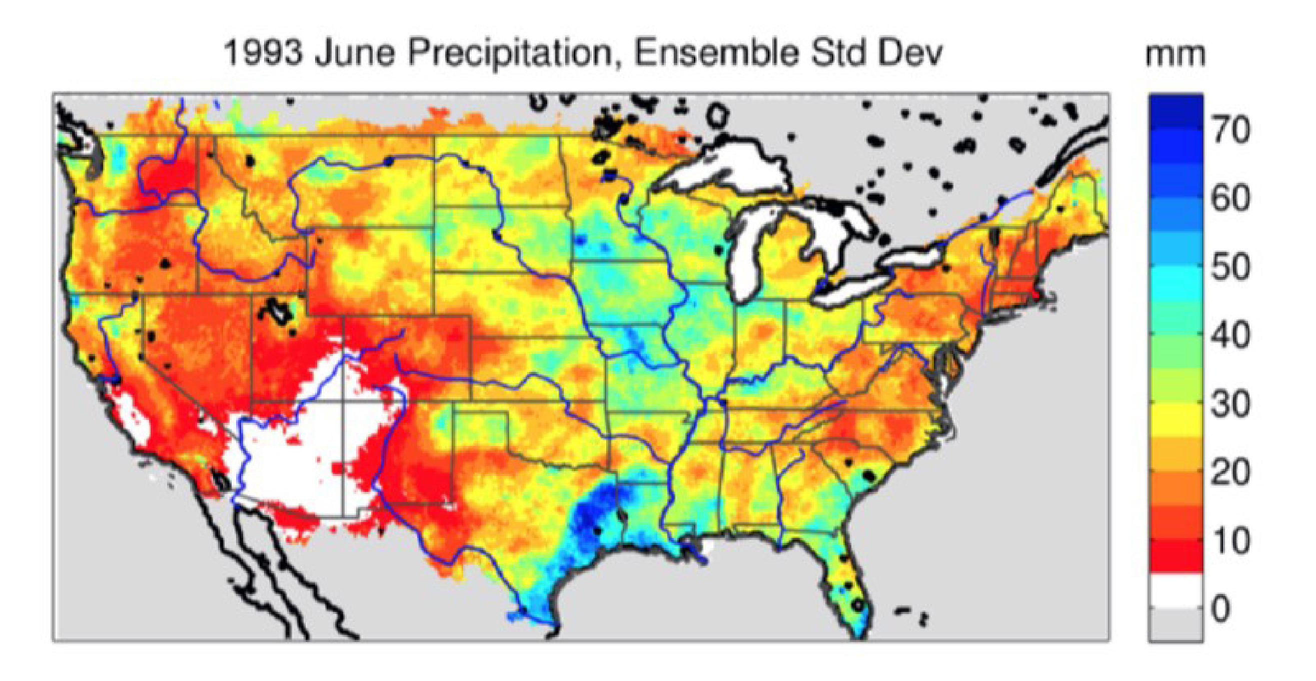
S&T Project page: www.usbr.gov/research/projects/detail.cfm?id=1620
NCAR Computational Hydrology: https://ncar.github.io/hydrology/

In recent decades, hydrologic modeling research and applications in the western U.S. have relied primarily on only a few watershed modeling options. Operational forecasting to support water operations has used the Snow17 and Sacramento Soil Moisture Accounting models. River basin sensitivity studies, climate change analyses, and seasonal forecasting research have used the Variable Infiltration Capacity (VIC) model. The Precipitation Runoff Modeling System (PRMS) has also been used for watershed analysis and forecasting.

Over the last five years, through multiple projects, Reclamation has helped to advance a new suite of process-oriented hydrological modeling and forecasting tools that provide a new option for hydrologic research and applications. The Structure for Understanding Multiple Modeling Alternatives (SUMMA) is a flexible hydrologic modeling framework (Clark et al, 2015) that has been configured for the Reclamation service domain on a USGS HUC12 watershed spatial fabric, delineating 54,701 individual watersheds (see figure below).



The HUC-12 based implementation of the SUMMA model in the western US, with a MERIT stream network implementation of the mizuRoute channel routing model. USGS gages collocated with the stream network are also shown (red dots).



Gridded precipitation ensemble standard deviation during the Mississippi River flood of 1993.

This initial west-wide implementation of SUMMA has 3 soil layers, up to 5 snow layers, and an aquifer component, a configuration that was designed to balance process complexity with computational suitability for applications. The mizuRoute channel routing model (Mizukami et al, 2015) offers several methods, and has been implemented for a several different channel networks, including rectilinear (as in the unit hydrograph routing commonly applied with VIC) and newer stream networks derived from the fine resolution NHDPlusV2 dataset and coarser the MERIT-Hydro dataset. Since the models were first published, substantial effort has been invested in continued debugging as well as enhancing the speed, efficiency and usability of models for different applications. Model application workflows have been created to enable calibration and visualization, and real-time forecasting and retrospective hindcasting. Additional supporting work has refined a key approach for developing model forcings, the Gridded Meteorological Ensemble Tool (GMET; Newman et al, 2015). The resulting datasets and model runs have a 3-hourly time step and span 50+ years – 1970 to present.

This work has resulted in a new major capability for hydrologic analysis and applications that is being used in a number of current projects, including ESP-based seasonal forecasting in the Rio Grande, the Shoshone and Tuolumne River basins, hydrologic predictability analyses west-wide, and snow-runoff relationships in the Bighorn River basin, and climate vulnerability analysis in the Columbia River basin. A CAMELS 761-basin model dataset has also been created for use in hydroclimate analysis, including training ML/AI models and for educational use in the NSF HydroShare project. The new models and data resources strengthen the hydrologic process modeling options available to Reclamation for investigating hydrometeorological questions relevant to managing water in the face of climate non-stationarity.

National Water Model

National Water Model Assessment for Reclamation's Water Management Needs

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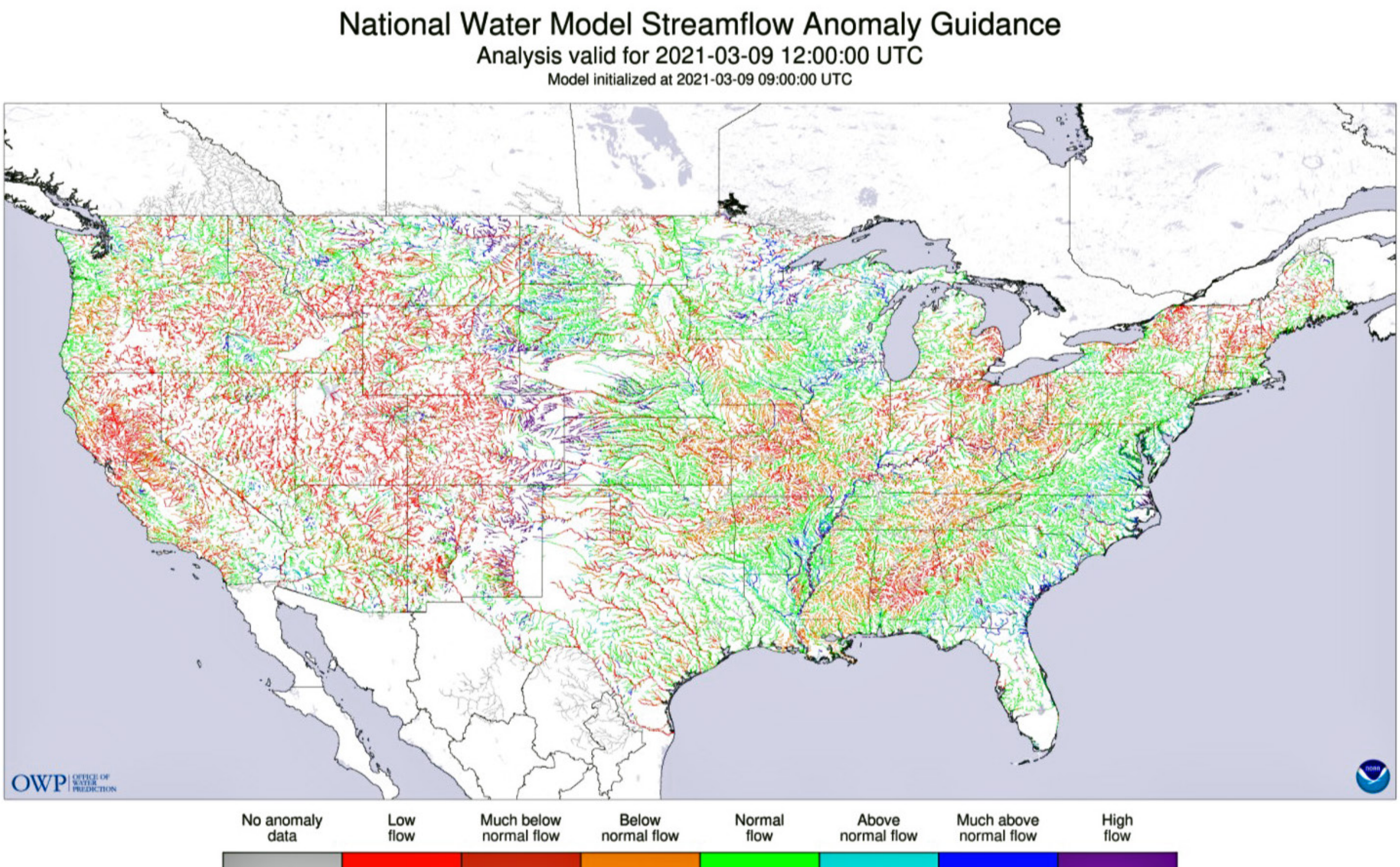
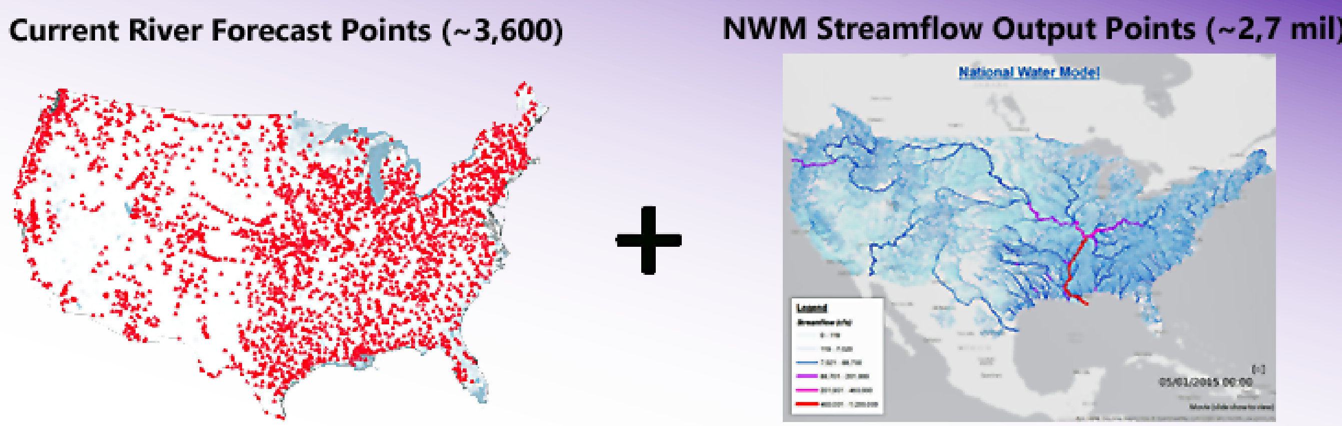
S&T Project page: www.usbr.gov/research/projects/detail.cfm?id=1774
About National Water Model: https://water.noaa.gov/about/nwm

In 2016, NOAA introduced a new, distributed streamflow forecasting system for the continental United States (CONUS), the National Water Model (NWM). Over the CONUS, NWM short-range forecasts are executed hourly and extend 18 hours into the future. The NMM also generates medium-range (10 day) and long-range (30 day) forecasts, each produced four times per day. All model configurations provide streamflow for 2.7 million river reaches and other hydrologic information on 1km and 250m grids.

This project provides both a quantitative and reflective assessment of the NWM for basins of interest to Reclamation. The assessment explores a range of forecast lead times. This is accomplished by evaluation of forecasts and retrospective simulations via a variety of skill metrics. Of note, the NWM includes simplistic reservoir operations and few diversions/depletions. Accordingly, most of the analysis focuses on largely unimpaired headwaters basins. Performance varied across the locations studied, but generally improved over the course of



Streamflow anomalies from National Water Model analysis on March 9, 2021 (image courtesy of NOAA NWC).



The NWM provides complementary hydrologic guidance at current National Weather Service (NWS) river forecast locations and significantly expands guidance coverage to previously unforecast locations (image courtesy of NOAA NWC).

the project as more basins underwent calibration efforts. However, in most cases, skill did not improve upon the performance of other available forecast products, such as those from the River Forecast Centers (RFC). Although skill metrics tended to show best NWM performance for snowmelt runoff conditions, anecdotes from discussions suggest that there may be utility for responding to rapidly changing conditions, given the high frequency with which the NWM updates.

In addition, the work explores the hydrology processes of a snow-dominated watershed, to better understand model fidelity and the utility of ancillary data products, such as distributed snow information. This investigation used historical forcing data with the model to simulate historical conditions, which were then compared with in-situ observations. When using the standard NWM CONUS historical forcing dataset (NLDAS), a significant negative bias in snowpack was noted. When forced with locally observed forcing data, biases were reduced. The radiation and precipitation components of the NLDAS forcing are suspected as the primary sources of the negative snowpack bias. However, in some cases, the observation-forced simulation still suffered from negative SWE biases, indicating other processes must be at play.

Another aspect of this project explored a potential methodology for generating ensemble NWM forecasts using a post-processed version of the Global Ensemble Forecast System (pp-GEFS) and compared to ensembles from the RFC Hydrologic Ensemble Forecasting Service (HEFS). While the HEFS ensemble was able to capture the observations more frequently than the experimental NWM ensemble, both captured streamflow observations less than 80% of the time using the central 80% of the ensemble envelope. This suggests that while the meteorological uncertainties may be captured well by the pp-GEFS ensemble, the uncertainties stemming from the hydrologic model may not be well represented during this process.

Development of the National Water Model in its current form continues and has yielded improved performance and additional functionality such as lagged-ensemble forecast products. In parallel, NOAA's Office of Water Prediction has undertaken a new effort to develop a community-based, Next Gen Water Modeling Framework, which could be the basis of future forecasting systems.

Federal Water Partner's Innovation in Water Supply Forecasting

A New Operational NRCS Snowmelt Runoff and Water Supply Forecast Model

By Sean Fleming
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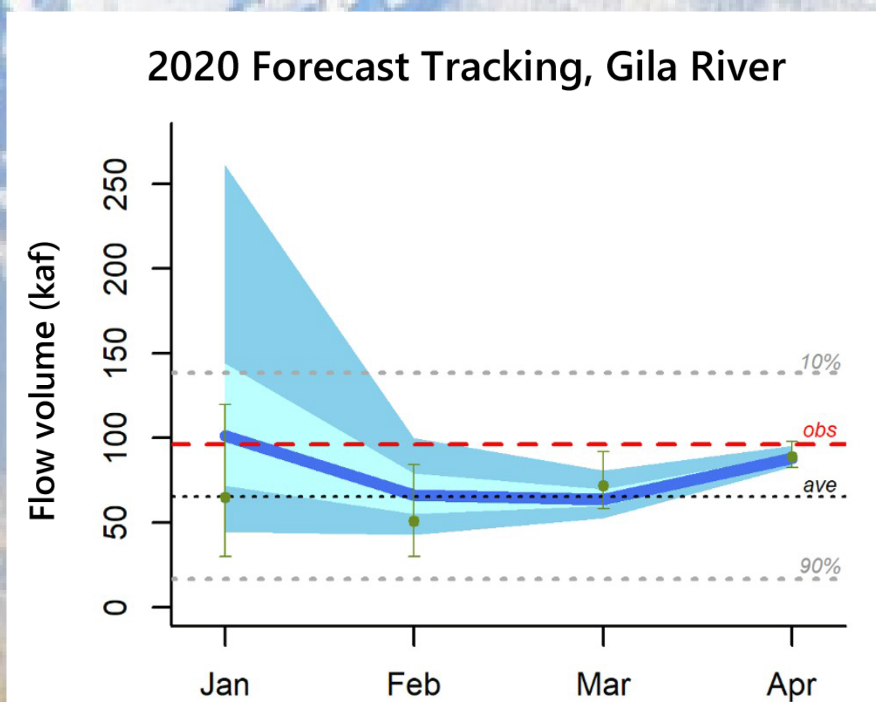
NRCS M⁴: www.wcc.nrcs.usda.gov/ftpref/downloads/factpub/wsf/FlemingAndGoodbody_IEEEAccess_2019.pdf

Melting of wintertime mountain snowpack provides the majority of the spring-summer runoff volume in most western North American rivers. This lag in turn enables useful seasonal runoff volume predictions at lead times of months, far longer than reliable weather forecasting horizons. In particular, operational water supply forecasts (WSFs) are predictions, typically issued once or more per month beginning in winter and based largely on snowpack measurements, of upcoming spring-summer flow volume for a given point on a given river, performed by institutions having direct accountabilities to end users around reliable generation of forecast products. These operational WSFs form the information backbone of the water management infrastructure in the largely dry western United States.

The USDA Natural Resources Conservation Service (NRCS) and its precursors have therefore monitored snowpack and produced operational WSFs in the region since the 1930s. NRCS runs the SNOTEL and SCAN networks and the largest stand-alone WSF system in the western US. Principal component regression (PCR) was first deployed by NRCS for WSF in the 1990s. Though successful and widely emulated, it has known technical issues and is showing its age. Capitalizing on prediction improvements potentially enabled by machine learning, we developed an AI-based approach as a prototype for the next generation of operational NRCS WSF model.

The overall design goal involved a pragmatic intersection between AI, hydrologic science, and operational prediction. The architecture is modular and multi-layered, and it integrates a careful selection of predictive analytics chosen to achieve specific practical design criteria. Foundational elements are a multi-model ensemble of six statistical and machine learning methods, each with associated probability models for estimating prediction uncertainty; and unsupervised statistical pattern recognition, combined with an evolutionary algorithm, for optimal feature extraction. Notable attributes include using hydrologic process knowledge to constrain AI solutions by imposing a priori requirements like non-negativity, deploying autonomous machine learning (AutoML) to facilitate use by operational hydrologists, integrating explainable AI to enable geophysical understanding of the modeled relationships and associated forecasts, and addressing known complexities including nonlinear relationships and heteroscedastic and non-Gaussian prediction intervals.

Application of the resulting prediction framework, the multi-model machine-learning metasystem (M^4), to 20 hindcast test cases spanning diverse hydroclimatic environments across the western US and Alaska, demonstrated both accuracy and usability advantages over the current system. Preliminary live operational testing for a subset of test cases during the 2020 forecast season confirmed logistical feasibility of associated real-time workflows and, of particular note given the so-called black-box reputation of machine learning, hydrologic interpretability of the prediction results, facilitating convenient 'storylines' for forecast communications. Both retrospective and operational testing confirm that, as intended, M^4 functions as an over-the-loop automated prediction engine that allows, but does not require, manual hydrologist intervention. Ongoing and future work involves development of a user interface, exploring integration of additional AI methods, testing high-dimensional predictive datasets like those from remote sensing and seasonal-to-subseasonal climate models, and extending M^4 into an inter-model and inter-agency forecast integration platform.



M⁴ example: operational forecasts during 2020 of January-May total forecast volume for the Gila River, a lower Colorado River tributary in southern New Mexico. Heavy blue line, light blue shading, and dark blue shading indicate best-estimate, 0.30 to 0.70 quantile prediction intervals, and 0.10 to 0.90 quantile prediction intervals, respectively. Green dots and error bars give best estimate and 0.10 to 0.90 prediction intervals from existing NRCS model, which has comparable accuracy to other operational WSF systems in the western United States. Final observed January-May 2020 volume is given in red, and summary statistics for historically observed values are provided in gray.

Risk Based Reservoir Operations

Can Risk-Informed Reservoir Operations Improve Decision-Making?

By Jordan Lanini, Marketa McGuire, with Project Partners; NCAR, & University of Colorado CADSWES
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Imagine you're responsible for setting Buffalo Bill Reservoir releases near Cody, Wyoming on May 1, 2015. Conditions for the last month have been warm and dry. You've seen this pattern before, in the early 2000s, when dry patterns continued into the summer. During that drought, decreasing releases in spring preserved storage. Your inflow forecasts, based on snowpack in the Shoshone River basin headwaters, projects low snowmelt runoff volumes. You judge the biggest management risk to be a dry spring and decide to reduce the reservoir release to try to preserve storage to supply future water needs.

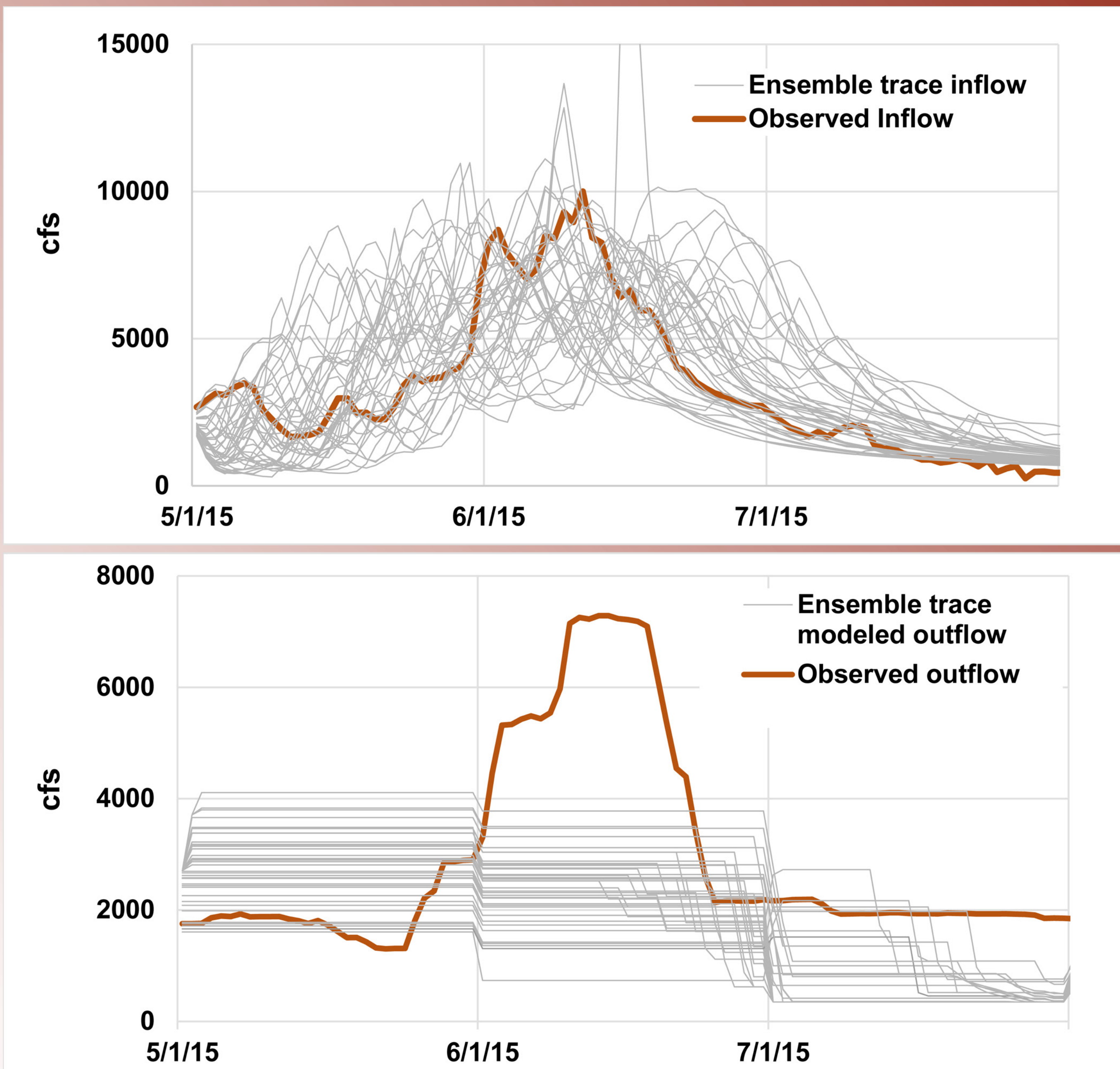
Was this the best decision? Probably, considering the limited forecast information available at the time. But with lots of uncertainty and only professional judgment to gauge risks, you may experience sleepless nights if the spring precipitation arrives higher than expected, forcing higher releases to avoid spilling water. For Buffalo Bill, the risks can also include insufficient storage for future water supply deliveries and diminished hydropower generation.

This decision scenario calls out for an objective procedure to quantify uncertainty and risk, informing decisions and, in theory, increasing project benefits. Typically, uncertainty information comes in the form of the 10% and 90% exceedance probability bounds on the median spring runoff volume forecast, augmented by comparisons to past year forecasts and runoff outcomes to indicate possible hydrograph timing. Risk is assessed by examining these bounds in a monthly operations model. Water supply forecast ensembles (a set of future inflow hydrographs generated from a rainfall-runoff model) also exist, but the best manner to use this information is not clear.

We are examining the opportunity to strengthen a data-driven foundation for managing risk. Hydrologic inflow uncertainty can be quantified by two sets of inflow forecast ensemble methods. The National Corporation for Atmospheric Research is using its SUMMA precipitation-runoff model to develop ensembles based on short-term weather forecasts and climatology to project future inflows. The hindcasts are bias-corrected and blended to prior observed flows. The Technical Service Center is disaggregating seasonal statistical forecasts generated with PyForecast to a daily timestep.

Risk is quantified with a RiverWare reservoir model representing reservoir operating policies (development led by Reclamation) to ingest the ensembles, making release decisions for each trace based on the operating policy. The Center for Advanced Decision Support for Water and Environmental Systems is developing a procedure to suggest better operating decisions. The procedure uses two stage stochastic programming with recourse. The operations model represents a range of possible releases for a week and examines the benefits and risks for those releases over the following year, across all ensemble traces. A pre-determined balance of risks and benefits (Developed with Wyoming Area Office) will guide release decisions each week, with the process updating with new forecast ensemble as operations march forward through the year.

This process will never completely replace the operator's professional judgement but will provide new quantitative information on the potential ramifications of release decisions. Hopefully, this helps operators get a better night's rest.



Ensemble forecasts provide more information on volume and timing of inflows. When combined with a model, operators can envision a much broader range of potential outcomes, leading to better decision-making. In 2015, ensemble traces indicated the potential for the late spring precipitation that resulted in high inflows. Representing these traces in the RiverWare operations model allows operators to determine a release that balances the various project benefits.

Lower Colorado Intervening Gain Forecast

Improving Short-Term Forecasts of Weather-Driven Losses and Gains on the Lower Colorado River

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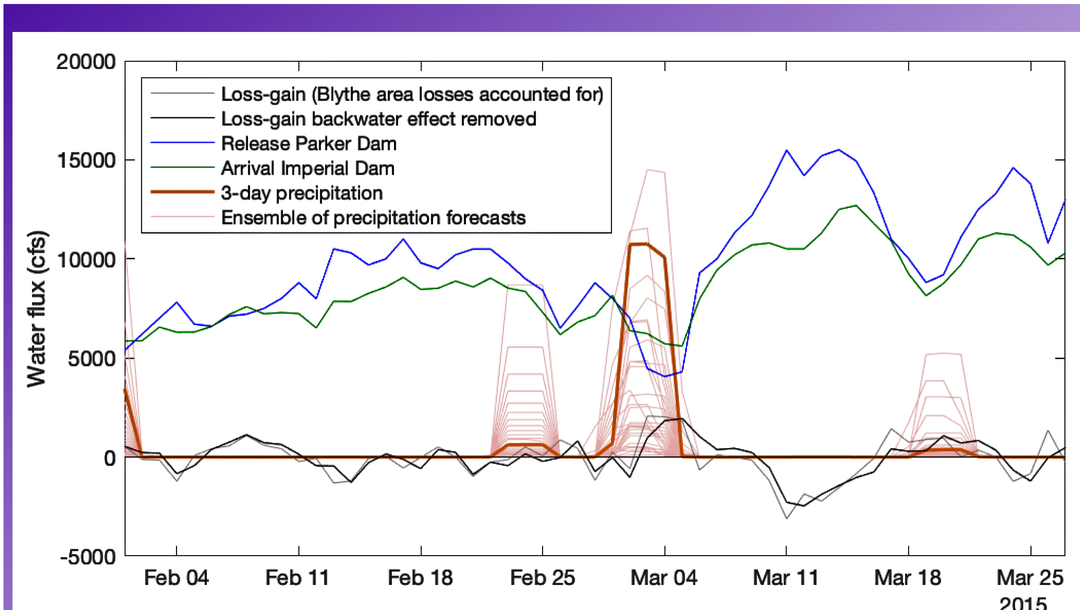
Reclamation's Yuma Area Office (YAO) in Yuma, Arizona, manages the last stretch of the Lower Colorado River before it crosses the border with Mexico. YAO navigates the many complex dependencies on the river on a daily basis, from deliveries to regional irrigation districts to water quality and volume regulations under an international water treaty. Despite detailed accounting of water releases and diversions from upstream dams and water users, unpredictable daily fluctuations in the amount water arriving in Yuma, termed 'losses' and 'gains', complicate YAO's operations. The YAO teamed up with the National Center for Atmospheric Research (NCAR) and the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado, to investigate the losses and gains and develop a forecasting tool to help anticipate them.

The project team first confirmed that major precipitation events can cause significant gains on the river stretch below Parker Dam (which dams Lake Havasu), leading to gains during the approximately 3-day water travel time from Parker Dam to the Yuma area. However, they also found that daily variations in the amount of water being released from Parker Dam can cause natural backwaters along the mainstem to fill and drain with the rhythm of the release schedule, leading to apparent – not real – losses and gains in the Yuma area unrelated to precipitation events. After correcting for these "artificial" losses and gains, the project team is now using a locally-calibrated version of the Global Ensemble Forecasting System (GEFS) precipitation forecast to predict the timing and magnitude of losses and gains from rain events.

This project template has the potential to be of wider use for Reclamation. Project collaborators managing water in the Middle Rio Grande, for which there is a 5-day travel time between the main water storage reservoir and water users, would also benefit from better short-term precipitation forecasts and characterization of losses and gains.



Example of losses and gains during and after a rain event in the Yuma area, including ensemble precipitation forecasts as well as water releases from Parker Dam and 3-day lagged arrival at Imperial Dam.

Featured Faces

Dagmar Llewellyn, Albuquerque Area Office, UCB Region

Dagmar Llewellyn, a hydrologic engineer and supervisor of the Water Management Division Planning Group in the Albuquerque Area Office (UCB Region), is passionate about finding ways to improve the way that Reclamation manages water in the Rio Grande Basin. Toward that goal, Dagmar has been active in the Science & Technology Program since 2015, and leads the involvement of her office in the S&T Program.

Dagmar's involvement with the S&T Program began at a training program on the development of hydroclimate projections at the National Center for Atmospheric Research, at which she and an NCAR researcher were discussing the ways that the processing of our hydroclimate projections led to masking of changes in extreme events. The two submitted a scoping proposal to apply extreme value theory to extreme-event changes in New Mexico, and continue to work together to this day on projects related to characterization of changes to, and forecasting of, the summer monsoons in New Mexico. Dagmar also works with colleagues at NCAR to characterize changes in spring snowmelt runoff, and improve forecasting of this important component of the water supply, as described in this issue of *The Knowledge Stream*.

Other research projects she leads or participates in involve monitoring of reservoir evaporation through floating evaporation pans, eddy covariance towers, processing of satellite data, and weather modeling. She also collaborates with NASA on a project to improve monitoring of crop and riparian evapotranspiration in the Rio Grande Basin. Her most recent collaboration involves the use of hydroacoustic sensors to detect streambed mobilization, to support environmental flows in the Wild & Scenic Reach of the Rio Chama.

Dagmar's enthusiasm for the S&T program is infectious, and she has encouraged a number of colleagues in her office to submit their own ideas to the program, and see how they can use science to improve the ways that Reclamation meets its mission.