National Aeronautics and Space Administration

NASA
WESTERN WATER
APPLICATIONS
OFFICE

Western Water Rapid Needs Assessment Report

Tools for managing a precious resource

December 2016

Executive Summary

The Western Water Applications Office (WWAO) is a new office of the NASA Applied Sciences Program headquartered at the Jet Propulsion Laboratory (JPL). Important goals of the WWAO are to make NASA observations and data more accessible to western water stakeholders to support western water management and decision makers in addressing water resource challenges. Key objectives of the WWAO are to strategically (i) connect stakeholders with NASA scientists, technology and data; (ii) develop custom solutions through applications projects; and (iii) assist transition of promising applications to operations or to the private sector.

A Review Board with a diversity of experience and perspectives in western water met at JPL on September 22-23, 2016 to review a Rapid Needs Assessment (RNA) developed by the WWAO staff that summarizes high-priority science and management needs in western water management. An important outcome of the RNA is to provide comments to the WWAO on strategic investment of time and resources. The objectives of the RNA are to assemble a preliminary catalog of needs which can be shared with interested NASA and non-NASA scientists and engineers; establish the basis from which projects for prioritized areas will be developed in the near term; and provide guidance for development of strategies to address high-impact long-term needs.

The RNA pointed to the following high-level needs of western water stakeholders

- Understanding and characterizing the transient nature of basin-scale hydrology and water balance, including interannual and long-term, climate-change driven variations
- Improving accessibility of NASA water observations and related data, in usable formats.
- Integrating wide-area satellite and aircraft observations with local- and basin-scale observations
- Developing and maintain a collaborative space in which to address these challenges with colleagues from other agencies

More specific needs were identified, including

- Characterizing changing rain/snow transitions and high elevation snow water content
- Improved evaporation and evapotranspiration information products
- Real-time soil moisture monitoring
- Groundwater inventories, capacity, inflow/outflow measurements
- Improved precipitation forecasting, including atmospheric rivers

This RNA focuses on water supply and availability, and consumptive water use. A subsequent report will examine water quality and water infrastructure needs. It should be noted that climate change, policy, and challenges of data accessibility and usability cut across all needs identified in this document.

1. Introduction

1.1 Background

This report presents the approach and results of a Rapid Needs Assessment conducted by the NASA Western Water Application Office (WWAO) to summarize the science and management needs for western water resources. The objectives of the Rapid Needs Assessment are to assemble a preliminary catalog of needs which can be shared with interested NASA and non-NASA scientists and engineers; establish the basis from which short-term projects for prioritized areas will be developed; and provide guidance for development of strategies to address high-impact long-term needs. An external Review Board was convened at JPL to provide review comments on the catalog and characterization of needs.

1.2 Context and Overview of Needs

The Western United States is defined by the Department of Interior (DoI) as those states that are on or west of the 100th meridian and encompasses the states represented by the Western Governor's Association (WGA). It is roughly the divide between the "wet" east and the "dry" west (Figure 1).

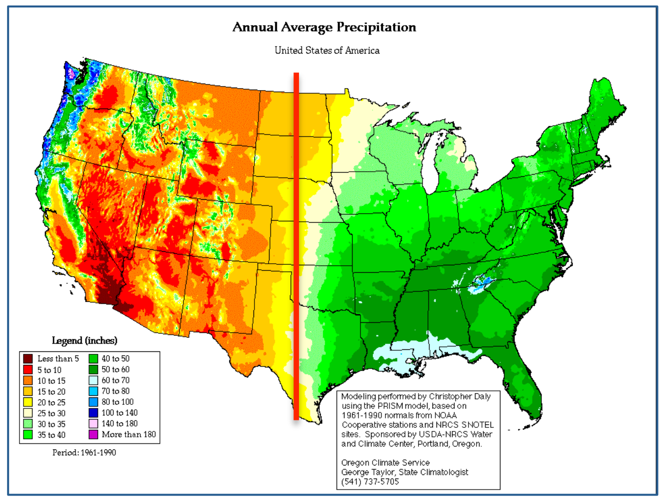

Figure 1 - ***A 30-year climatology of annual U. S. Precipitation. The red line denotes the 100th meridian. (Source: C. Daly, Oregon State University)***

Specific needs are described here in terms of four categories: (i) Water Supply and Availability; (ii) Consumptive Water Use; (iii) Water Quality and; (iv) Water Infrastructure.

(i) Water Supply and Availability; (ii) Consumptive Water Use needs are addressed here; a subsequent assessment will examine (iii) Water Quality and; (iv) Water Infrastructure. **It should be noted that climate change, state and federal policy decisions, and challenges of data accessibility and usability cut across all needs identified in this document.**

1.2.1 Western Water Resources Management and Community

Water resources in the western U. S. are managed by a number of Federal and non-Federal entities that includes individual tribes, states, irrigation districts, utilities, and municipalities [1]. Water is managed for a set of often competing purposes including ensuring a sustainable water supply, providing hydropower, recreation, flood management, and ecosystem restoration. To support this array of requirements, the agencies noted above provide services that include collecting and disseminating monitoring information, providing analysis, and developing forecast products at different time scales and spatial resolution.

The end result is a complex interaction of responsibilities, legal frameworks, and stakeholder needs, guided by uncertain information [1] that is essentially bounded by how the extremes – floods and droughts – are defined and characterized, along with methods and standards for reducing risks [2].

Water decisions in the arid West are increasing in complexity as pressure on existing supplies continues to grow [3] due in part to population growth [4], environmental considerations, and changes in hydrology due to a changing climate [5][6][7]. Because of the importance of water, considerable resources are already invested in data and tools for managing water in the west [4]. However, the existing paradigm of water management faces significant challenges including inadequate funding to maintain and upgrade monitoring networks, lack of resources to integrate new data sources into existing tools, and demands for improved spatial coverage of observations [7]. The changing hydrology of the West is so complex that it requires measurements and analyses that have never been done before, and increases the importance of verifying existing models [7].

1.2.2 The Role of NASA's Western Water Applications Office (WWAO)

The WWAO is a new local western office of the NASA Applied Sciences Program headquartered at the Jet Propulsion Laboratory (JPL) to put NASA data to work in decision support for western water management. The objectives of the WWAO are to: (i) connect stakeholders with NASA scientists, technology and data; (ii) develop custom solutions through applications projects; and (iii) assist transition of promising applications into an operational state.

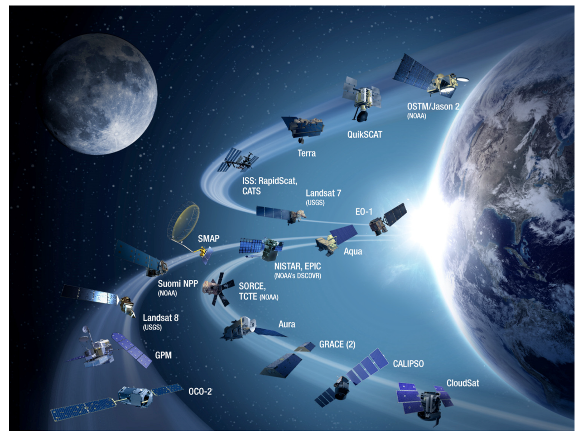

Figure 2 - NASA Earth science fleet of satellite missions

NASA has an unprecedented suite of capabilities, including 19 satellite remote sensing missions that can complement and add value to the Nation's substantial investments to enable the provision of actionable information about water availability, extreme events, water quality, and infrastructure integrity.

1.3 Goal and Objectives of the Rapid Needs Assessment

The goal of this Rapid Needs Assessment is to summarize the science and management needs for western water resources in which NASA observations and research can play a role. Objectives of the Rapid Needs Assessment are to:

- Assemble a preliminary catalog of needs which can be shared with interested NASA and non-NASA scientists and engineers;
- Establish the basis from which short-term projects for prioritized areas will be developed; and
- Provide guidance for development of strategies to address high-impact long-term needs.

2. Glossary of Acronyms

ADWR Arizona Department of Water Resources

CBRFC Colorado Basin River Forecast Center

CDWR California Department of Water Resources

ET Evapotranspiration

GRACE Gravity Recovery and Climate Experiment

MWD Metropolitan Water District

NASA National Aeronautics and Space Administration

NIDIS National Integrated Drought Information System

NOAA-NWS National Oceanographic and Atmospheric Administration – National Weather Service

RFC River Forecast Center

RNA Rapid Needs Assessment

SNOTEL Snowpack Telemetry

S2S Sub-seasonal to Seasonal

SWE Snow Water Equivalent

USACE United States Army Corps of Engineers

USBR United States Bureau of Reclamation

USDA-NRCS United States Department of Agriculture – Natural Resources Conservation Service

USGS United States Geological Survey

WSWC Western States Water Council

WWAO Western Water Applications Office

3. Methods

A “Rapid Needs Assessment” is a specific form of needs assessment that involves using existing assessments, journal articles, workshops, and surveys to undertake a relatively quick, easy and inexpensive snapshot of a specific community in order to assess the needs of planned initiatives. Needs assessments are a staple of the international development community where they are used as a planning tool to develop programs and specific interventions. The WWAO adapted aspects of the Rapid Needs Assessment construct to quickly identify management needs, as well as the challenges and gaps in meeting those needs for the western U. S. water resources landscape.

The central question for the WWAO is: “What are the impediments to making better decisions about water in the West, and which of these can NASA and the WWAO help solve?” By design, this is phrased as a stakeholder-centric question rather than a research-centric or NASA-centric question. The goal is develop a push-pull model that matches NASA capabilities to high-priority stakeholder needs and questions. This report is driven by the question: “What do stakeholders need most in order to do their jobs better?” rather than, “What resources does NASA have that might help stakeholders?”

The assessment builds on published assessments, journal articles, white papers, congressional reports, workshop reports, and an informal survey of western water managers conducted in 2014 following a joint NASA and Western States Water Council Remote (WSWC) Sensing workshop. Several priorities emerged during the 2014 workshop and were further elaborated upon through an informal survey of participants following the workshop. Most of the respondents expressed interest in improved/ higher resolution evapotranspiration (ET) products and improved access to ET products. Needs for snowpack quantification and observations, and improved groundwater monitoring were also identified. A summary of responses organized by water supply, consumptive use, water infrastructure, and water quality are given in Appendix B.

Management needs are described in terms of four categories: (i) Water Supply and Availability; (ii) Consumptive Water Use; (iii) Water Quality and; (iv) Water Infrastructure. Within each category, topical needs are identified, with specific management and information needs described for each area. Water supply and availability, and consumptive water use are addressed here, a subsequent report will examine water quality and water infrastructure needs. **It should be noted that climate change, policy, and challenges of data accessibility and usability cut across all needs identified in this document.**

Needs are classified into near-, medium-, and long-term needs where a near-term is defined as a capability needed and deliverablewithin the next 1-2 years, medium-term is 3-5 years and long-term is 5-10 years. Classification of the timeliness of needs is subjective, taking into account how likely decision makers are to use the results, the level of difficulty, technical maturity, time investment required, potential impact, and stakeholder interest.

Review and feedback are important components of the needs assessment process. To this end, an external review board was convened at the Jet Propulsion Laboratory September 22 and 23 2016 to provide feedback and guidance on the assessment. The board represented a broad spectrum of experience in western water resources, and was made up of experts in hydrology, decision support and western water policy from academia, state and local water organizations, and federal agencies with a mandate for managing water in the west. Results of the board discussion and review are incorporated into this report. A list of review board participants is given in Appendix A.

4. Western Water Resources Management Needs

From a high-level perspective, stakeholders need assistance with:

- Understanding the changing hydrology, largely at the basin scale;
- Integration of wide-area observations with local- and basin-scale observations, data standardization that would allow additional data to be assessed;
- A collaborative space in which to address these challenges with colleagues from other agencies; and
- Data standardization.
    - While a great deal of data exists, formats are not standardized.
    - Each state gathers data differently.
    - Even the definition of "water use" differs among states.
    - Much of these data are not digitized.

There is a strong desire to increase basic knowledge of hydrology in the Western States and how that hydrology is changing. Unlike the academic research community, water resource management stakeholders need to apply fundamental science to practical challenges at regional, basin, and local scales to develop long-lasting solutions to water challenges [9] including:

- Changing rain/snow transitions and high elevation snow water content;
- Improved evaporation and evapotranspiration measurements;
- Real-time soil moisture monitoring;
- Groundwater inventories, capacity, inflow/outflow measurements;
- Improved precipitation forecasting;
- Validation of existing models with in situ observations.

Although improving forecast and other models is a long-term goal, it can be hard to achieve for many reasons, including the lack of resources to incorporate new data into existing model environments. One near-term solution is to visualize existing data to increase their utility for decision support. Since managers adjust model-based forecasts on additional data sources that the models cannot accommodate, having additional data is useful even if it cannot be integrated into the model, and visualizations can often do more to help educate policymakers than data analysis and expert predictions.

4.1 Water Supply and Availability

4.1.1 Snow, Watersheds and Runoff Forecasting

Although the percentages vary from basin to basin, about 50-80% of water in the American West comes from snowmelt. Estimates of runoff from snowmelt are used to make allocation decisions and forecasts for water supply (municipal and agricultural), hydropower, drought mitigation, recreation, environmental sustainability, and flood potential [10]. In systems that rely heavily on snow water supplies, changes to snow depth and snowmelt rates may impact the timing and quantity of runoff, ultimately impacting the availability use of water in those regions. [11][12][13]

Observations of snowpack are derived from a long-standing network of point measurements that are relied upon to (i) understand the evolution of basin snowpack during the snow year and (ii) drive models that estimate and predict run-off from snow [10][14][15].

Challenges and gaps: There is no one-size-fits all solution to improved run-off prediction in snow-dominated systems in the western U. S. because there is significant variation in watersheds and basins across the west in terms of physical characteristics, existing monitoring systems, and in management and data priorities.

In rural basins like the Upper Snake and South Fork of the Shoshone, data collection sites are limited because of federal protection as wilderness areas, and maintaining these sites requires multi-day trips to access them. When one of these stations goes down, it is difficult to make accurate forecasts because there may be few (or no) sites in the vicinity that can be used. Lower elevation basins, like those in eastern Montana, are rain dominated and are hard to forecast based only on measured snowpack, while other basins, particularly those in the Cascades and Sierra Nevada lie in the transition zone between rainfall and snowfall making forecasts there difficult. A challenge common to these basins is that the transition zones are moving upslope across the entire western U. S..

In the Kings River basin in California, data acquisition efforts are hampered by access to the wilderness area, and the steep and rugged terrain. There are limited ground stations and snow course information, yet having data on precipitation and snowmelt are key to managing the resources through Pine Flat Reservoir for use in the downstream region. The Kings River's service area of one million acres is a land served by 28 dedicated agencies that deliver water from the Kings River and other sources to agricultural users in the San Joaquin Valley.The Kings River Water Association and the Kings River Conservations district would benefit from access to additional data sources. The National Park Service and U. S. Forest Service could benefit as well.

Moreover, timing of the runoff depends not only on snow depth and volume, but also on precipitation rates, temperature, forest/vegetation, land use, and soil moisture, all of which can differ early and late in the season. Forest fires can dramatically change vegetation that in turn can change the timing of runoff. Another factor throughout the west, and especially in areas with growing population and changing land use, is increased dust on snow that impacts albedo and changes how the snowpack melts off in the spring.

Lastly, watersheds are changing in unprecedented ways and managers are uncertain what this will mean in the future because no historical measurements match what is happening today [7]. The processes and tools by which we manage water in the west were designed to measure seasonal changes not to account for climate change. In a changing climate there will be more water in snow at high elevations, but there are few monitoring systems at those elevations [6][12][16]. And the peak of the snow season in the

American West is coming earlier, impacting reservoir management practices and run-off models.

Priorities and Needs:

- Albedo (dust on snow) and its influence on runoff timing;
- Information about snow pack at higher elevations than is currently monitored;
- Soil moisture and its influence on runoff volume and timing; and
- Climate change forecasting for watersheds on timescales of 10-50 years is a significant challenge for which stakeholders need new planning tools.

Table 1 lists specific management and associated information needs linked to stakeholders and the time frame for the need.

Management Need	Information Need	Stakeholder(s)	Time Frame
Improved understanding of how the snowpack is evolving in western U. S. mountain basins during the snow season to anticipate and plan for runoff anomalies. [13][17]	Weekly maps of basin-wide snow depth Weekly maps of basin-wide snow cover extent Weekly maps of basin-wide now water equivalent (during snow season) Weekly maps of basin-wide soil moisture Monthly maps of land use/land cover.	NOAA, USDA-NRCS Western Mountain States	Near-term
Incorporate information about dust on snow as images, with an indication of how the current year compares to past years and the average for dust. (14)	Weekly anomaly maps of snow albedo for critical watersheds in the Colorado River Basin. Weekly maps of average snow albedo for critical watersheds in the Colorado River Basin	CO Basin RFC, Colorado Dust on Snow Program (http://www.codos.org/#codos)	Near-term
Development of interactive snow analysis products to characterize basin-distributed snow- covered area and snow water equivalent. [5, 15]	Interactive mapping tool that integrates remote sensing observations and traditional measurements.	Western Mountain States, Utilities, Municipalities	Medium-term
Support flood control through assessment of springtime flood risk in the Great Plains states by broad-scale monitoring of snowpack. [15](22]	Spatially consistent monthly maps during the spring of: snow depth, snow cover extent, snow water equivalent	Plains States, Utilities, Municipalities	Long-term
More accurate seasonal predictions of the timing and magnitude of snowmelt in mountainous regions and their impacts to western water supply. [15]	Update existing operational modeling systems to assimilate gridded snow data including calibration Evaluation/validation of model output with assimilation of new science data products.	<u>Forecast modelers</u> NOAA-RFC's, USDA-NRCS <u>Information users</u> USBR ,USACE Utilities, Municipalities	Long-term

4.1.2 Monitoring Groundwater and Subsidence

Groundwater is the major source of water for many rural areas in the West, as well as an important ecological asset [18]. Groundwater -dependent ecosystems are sensitive to groundwater levels; small amounts of pumping cause big problems [19].

The U.S. Geological Survey's Groundwater Resources Program supports large-scale multidisciplinary studies of groundwater availability across the United States including more than 20,000 observation wells in cooperation with other entities [20]. However, as aquifers are depleted [21], it is increasingly important to improve our ability to monitor groundwater supplies. Many local agencies measure their own groundwater resources *in-situ*, which is insufficient for large areas and have spatial and temporal gaps in the data.

Challenges and gaps: A key area to understand is the use of groundwater aquifers both as primary water sources and as water storage facilities. As a primary water source, improved understanding of the water volume available for use in each aquifer, as well as the natural recharge rate of the aquifers is needed. As a water storage facility, information on the storage volume, limits on fill and withdrawal rates, and potential loses between the volume input and the volume that can be withdrawn is needed.

When using groundwater, operators must have information to help them avoid undesirable effects. In California, for example, these are defined as "One or more of the following effects caused by groundwater conditions occurring throughout the basin[1]":

1. Significant and unreasonable reduction of groundwater storage.
2. Significant and unreasonable seawater intrusion.
3. Significant and unreasonable degraded water quality, including the migration of contaminant plumes that impair water supplies.
4. Significant land subsidence that substantially interferes with surface land uses.
5. Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water.
6. Subsidence as a result of drawing down aquifers can impact infrastructure and aquifers may lose capacity for recharge. Groundwater pumping is causing it to some degree, but other factors are also involved.

One other key point is that surface water and groundwater are typically managed separately even though they affect each other. There may be a significant lag time in response of surface water to groundwater use, which makes it difficult to determine cause and effect. However, some western states employ conjunctive use management of surface and groundwater. To implement a program of conjunctive use, it's important to understand the aquifer storage capacity, production capacity of the aquifer in terms of discharge, the natural recharge of the aquifer and the potential for artificial recharge.

Lastly, increased incidence of earthquakes and impacts to water quality related to groundwater injection and fracking are also of concern to water managers.

Priorities and Needs:

Stakeholders lack and need a comprehensive understanding of groundwater resources in the West to answer:

[1] http://www.water.ca.gov/groundwater/sgm/pdfs/SGMA_%20GSP_Topic-1_PreSGMA_Conditions_Undesirable_Results.pdf

- How much groundwater is there in the west?
  - Remote sensing has been used to monitor groundwater storage volume and subsidence, yet a comprehensive picture of groundwater flows is lacking.
  - At local scales, remote sensing data lacks the necessary resolution (e.g., GRACE) and must be downscaled,
  - Remote sensing data used to monitor groundwater should be augmented and validated by local sensors,
- How to avoid chronic groundwater loss?
  - Measurements to mitigate the 6 undesirable effects of groundwater use.
- How can conjunctive use programs be optimized?
  - Improved understanding of the ratio between extraction and recharge at basin scales because:
    - Subsidence reduces storage capacity;
    - Groundwater "water banks" are inherently leaky.
    - Improved measurements of discharge;
    - Fundamental science is needed to accurately assess and measure these phenomena, e.g., there is little understanding of what is changing over time.

Specific needs are given in the following Table.

Management Need	Information Need	Stakeholder(s)	Time Frame
Need to prevent the six undesirable effects of groundwater use		USGS, Local agencies, Utilities, Municipalities, County, State, NGOs	
1. Loss of storage [26][27][28]	Loss of storage vs amount of water used		Near-term
2. Land subsidence [22][23][24][25]	High resolution and accuracy topographic information.		Near-term
3. Seawater intrusion	Loss of storage vs amount of water used		Near-term
4. Depletion of supply	Water volume available for use		Mid-term
5. Degraded water quality			Mid-term
6. Impact to surface water [29][30]			Long-term
Improved understanding of available groundwater volume [23]	Water volume available for use		Mid-term
	Natural recharge rate (perhaps from InSAR data)		Long-term
	Use rates		Long-term
Improved understanding of how aquifers can be used for water storage [26][27][28]	Available storage volume		Mid-term
	Fill rates (typical, minimum, maximum)		Mid-term
	Losses of water in vs water out		Long-term
	Withdrawal rate (typical, minimum, maximum)		Long-term
	Economics of storage		Long-term
Earthquakes			Long-term

4.1.3 Sub-seasonal to Seasonal (S2S) Precipitation Forecasting

Water resources management, particularly in the West, is bounded by how weather extremes such as floods and droughts are defined and characterized, along with the methods and standards for reducing risks [2][31]. Seasonal precipitation forecasts are needed to improve water supply reliability for managing extremes (e.g., floods and droughts), making emergency preparedness decisions, and for maintaining ecological benefits [12][29][30]. Sub-seasonal precipitation forecasts are a necessary tool for flood management, more efficient resource and reservoir management, and for making water allocation decisions [33].

In the western U. S., precipitation can vary tremendously between dry and wet years compared to the eastern United States, where as much as 85% of the variability can be attributed to the wettest 5% of days per year. Given this variability, improved S2S precipitation forecasting is critical to water and flood management.

Western U. S. stakeholders are collaborating with the research community on developing and implementing a new generation of forecasting and decision support tools that address extreme precipitation and flooding events in the western United States [32]. Improved Sub-seasonal to Seasonal precipitation forecasting was identified as a goal in the 2016 White House Federal Action Plan of the National Drought Resilience Partnership[2].

Challenges and gaps: The current scientific capability for forecasting beyond the ten day time horizon and at the S2S timescales important for water management is not sophisticated enough to support water management decision-making [33]. The probabilistic nature of forecasting is challenging to incorporate into decision-making – in some cases, water managers need to be educated on the role of uncertainty, utility, and expected values in probabilistic forecasts. Available S2S products do not always fit easily into institutional decision-making frameworks, and managers need forecasts of variables at resolutions that are more directly relevant to their contexts [33][34].

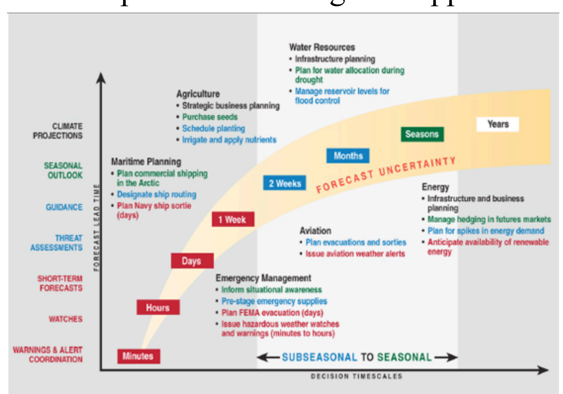

Figure 3 - S2S forecasts (blue & green) fill a gap between weather and ocean forecasts (red), and longer-term projections (black) and help inform decisions across multiple sectors (also blue & green). SOURCES: Earth System Predictability Office, [44]

Timing is an important factor in increasing usage of S2S precipitation forecasting by stakeholders. Agricultural water users have single-season outlooks; municipal water users have multi-year outlooks. Ideally, forecast times would align with resource management decision points; as such, it is important to understand the water manager "decision calendar" (Figure 2) and what aspects of a forecast can be structured to serve water management objectives over different time frames [12].

Where reservoir management requires year-round balancing of flood control with other purposes, changes in the magnitude, severity and intensity of extreme runoff require changes in operating rules to better manage flood risks while maximizing storage. Sediment transport is another consequence of extreme runoff that heavily impacts reservoir capacity and the ability to store water in the future [12].

[2] https://www.whitehouse.gov/the-press-office/2016/03/21/presidential-memorandum-building-national-capabilities-long-term-drought

S2S precipitation forecasting also needs to be better understood in the context of larger issues such as the complexity of the water cycle and the effects of climate change. Water resource managers already struggle with balancing flood control and water supply – climate change may exacerbate this challenge.

Priorities and Needs:
Skillful sub-seasonal to seasonal precipitation forecasting is needed to support water management in the western U. S. to provide lead time in preparing for extreme events and to allow for more efficient operation of water infrastructure [47]. Although improving the overall skill of S2S precipitation forecasting is a long-term research effort, incremental advances in S2S forecasting could have significant impact on water management in the near-term. For example improved understanding of processes or events that are regionally important contributors to seasonal precipitation offers promise for water management. Examples of these are Madden Julian Oscillation (MJO), monsoons in the Southwest, and AR events in California and the Pacific Northwest [47].

Predicting AR events is of particular importance as atmospheric rivers not only cause wide spread flooding throughout the U. S., they also supply 30%-50% of the precipitation along the U. S. West Coast [48]. Much of the variability in precipitation in the western U. S. is related to AR events. Improved predictability of AR's could play a crucial role in reservoir management – without improved prediction skill of ARs and the use of this forecast information, more reservoir water will typically be released than is necessary to maintain flood protection or to mitigate drought. As an example, in December 2013, a storm greatly increased the amount of water held Lake Mendocino in Sonoma County, California. In response the Army Corps of Engineers released water according to its Water Control Manual (circa 1959) for that reservoir, however, the release was followed by severe drought conditions from which the region has yet to recover[3]. Improved S2S precipitation forecasting, and of particular importance in the western U. S., improved AR forecasting could help to enable forecast-informed reservoir operations (FIRO) which could have prevented the loss of critical water supply from Lake Mendocino [2]. Most current operating rules for reservoirs exclude the use of forecasts, resulting in less efficient water management practices. A collaborative pilot project with the Sonoma County Water Authority, the Center for Western Water and Weather Extremes (CW3E) at Scripps Institute of Oceanography U. C. San Diego, the California Department of Water Resources, the U. S. Army Corps of Engineers (USACE), USGS, and NOAA seeks to demonstrate the viability of FIRO to the USACE. This project has the potential to significantly impact the way reservoirs are operated in the U. S..

This and other information needs are given below.

Management Need	Information Need	Stakeholder(s)	Time Frame
Improved forecasts including accurate probability estimates over the range of interest that allows water manager to properly manage reservoirs [2]	Long-term (~20 years) records of hindcasts based on present-day forecast capability to assess skill and uncertainties of forecasts at S2S lead times (e.g. 2 week to 6 months).	USACE, CDWR	Near-term

[3] http://cw3e.ucsd.edu/FIRO/

Regional scale observations of extreme precipitation. [33]	Including snow versus rainfall and that characterize topographic variations/forcing.	NOAA	Medium-term
More reliable precipitation forecasts to inform water supply and flood control operations at reservoirs where atmospheric river events frequently and predictably occur [32]	Improved understanding of sources of S2S predictability and how these lend themselves to forecasts of opportunity. Improved model representations of sources of S2S predictability (e.g. MJO, ENSO, snow, soil moisture).	USACE, USBR	Medium-term
Increase the skill S2S precipitation forecasting for western water management. [2]	Improved global and regional observations related to sources of S2S variability (e.g. global circulation to regional snow pack) – see NAS 2016 report and improved global prediction models.	NOAA, WSWC, State Water Agencies: CA, others	Long-term

4.1.4 Soil Moisture

Summary. Information on soil moisture variability is important for a number of applications including hydrologic modeling, weather prediction, and flood as well as drought monitoring [40][41] [51]. Soil moisture estimates are important for agriculture for irrigation scheduling and assessing suitability of a field for farm operations. Soil moisture information could contribute significantly to improved estimates of evapotranspiration and elements in the water cycle, including runoff projections, and assessing the impacts of climate change. Additionally, soil moisture is a critical variable for estimating potential for flooding. During periods where soils are highly saturated, water may not be able to be moved quickly enough to satisfy flood control needs.

Challenges and gaps: Ground-based observations of soil moisture in the United States at available at state-level climatic networks in Illinois, Oklahoma, Nebraska and West Texas and are available via the Soil Climate Analysis Network (SCAN) [42]. However, there are no consistent measurement standards [43] between the newer and older sensors and the network itself is still relatively sparse. Because of the challenges, soil moisture observations are not yet integrated into forecast models, yet have a profound impact on runoff, storage, and flood control.

Priorities and Needs: Soil moisture as a measurement is a gap, that if filled, could significantly improve understanding of water supply and demand variables, especially as a contribution to a number of modeling efforts through assimilation. Two examples of needs in the near-term at different spatial scales are given here with an additional long-term need provided in the table below. At the continental scale, the USDA and the National Integrated Drought Information System (NIDIS) have established a partnership to develop a coordinated national network focused on soil moisture with the goal of developing an integrated national soil moisture network[4] as part of the National Drought Resilience Partnership[5]. There is a need for spatially consistent soil moisture observations to support this effort. At local scales, soil moisture observations at the watershed level can provide valuable insight into watershed conditions that can have a significant impact to the amount of runoff, when soils are dry, nearly 80% of precipitation goes into the soil, while runoff into the reservoir is increased if soils are wet. As an example, a near-term strategy to improve efficiency of reservoir operations under consideration by the Sonoma County Water Authority in California is to monitor watershed conditions (soil moisture and precipitation) to inform reservoir management [50].

Management Need	Information Need	Stakeholder(s)	Time Frame
Understanding of watershed conditions for reservoir operations [2]	Soil moisture observations at watershed scales.	USACE, BoR	Near-term
Integration of soil moisture observations to advance the National Soil Moisture Network	Surface soil moisture at continental scales	USDA-NRCS, NOAA, USGS	Near-term
Irrigation planning	Real-time (daily) soil moisture at the root zone.	Federal and State, Individual farmers	Long-term

[4] http://www.westernstateswater.org/wp-content/uploads/2012/10/WestFastNews-2016-May.pdf

[5] https://www.drought.gov/drought/what-nidis/national-drought-resilience-partnership

4.2 Consumptive Use

4.2.1 Evapotranspiration

Summary ET is a primary component of hydrological balances in most ecosystems [46] and can be used operationally as a way to monitor crop water demand in agricultural areas or evaporative water loss over reservoirs. Agriculture represents up to 80% of water use in the U.S., with estimates exceeding 90% in many states in the western U.S.[6] In 2005, the USGS reported that the western United States accounted for 74% of surface and groundwater withdrawals for agriculture, though average annual precipitation in each Western State was less than 20 inches per year (and would otherwise be insufficient without supplemental water to sustain agricultural uses)[7]. Furthermore, most states in the western U.S. track diversions and allocations, but do not have a statewide program for tracking consumptive uses or return flows[8] [34][35]. This variability in how states or districts monitor consumptive use results in uncertainty for estimating current and future demands for water, as well as future availability.

Challenges and Gaps. Fundamental gaps exist in understanding of the spatial and temporal characteristics of evapotranspiration over large spatial extents [44][45] as the ability to measure, estimate, and model ET, particularly at the watershed and field scales, is still limited [46]. Although numerous methods have been developed to measure or quantify ET and its components, direct measurement of ET, in most cases, is not feasible.

Priorities and Needs:
Stakeholders lack and need a comprehensive understanding of the transient water balance in the western U. S. and especially for specific watersheds. More accurate estimates of evapotranspiration would both advance understanding of environmental and agricultural water needs and inform a more accurate understanding of water availability (and, thus, hydrologic forecasts, soil water capacities, groundwater recharge estimates, water for habitat and species biodiversity, and climate studies) [34][35] One of the specific needs identified is an operational ET product that is spatially and temporally consistent and able to resolve agricultural fields depending on the application. Other needs include an operational product that monitors losses of water into the atmosphere over open reservoirs, aqueducts and rivers, and the provision of ET for rangeland monitoring.

Remote sensing has considerable potential to supplement existing methods for understanding water demand from agricultural consumptive water use and losses due to evaporation from surface water bodies or reservoirs [36][37]. More work is needed to develop an operational ET product that utilizes satellite data and supports the capacity development to use these products for irrigation scheduling or other management practices.

Specific questions stakeholders need to address are:

- How much water is available for use?
  - Managers need a comprehensive forecast of seasonal surface water
- What is the natural evapotranspiration (ET) and how is it changing?
  - ET modeling accuracy has never been verified to the level that stakeholders would like to have.

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[6] http://www.ers.usda.gov/topics/farm-practices-management/irrigation-water-use.aspx)
[7] http://water.usgs.gov/edu/wuir.html
[8] http://www.westernstateswater.org/wp-content/uploads/2014/06/Western-State-Water-Program-Capabilities-Assessment-Survey-Report-FINAL-June2014.pdf

    - Better precipitation measurements are key to understanding natural ET.
    - Better measurements of evaporation from reservoirs and rivers are also needed.
    - Top data priorities (e.g., ET vs. precipitation) vary from basin to basin.
- How can stakeholders quantify the competing uses of water?
    - Both allocations and enforcement of allocations should rely on accurate data rather than inference.

Management Need	Information Need	Stakeholder(s)	Time Frame
Mapping irrigated lands as well as crop type and fallowed land. [36]	Spatially consistent annual maps of crop classifications, crop specific ET at field scale and fallowed land.	Western State Agencies	Near-term
Improved estimates of field-scale evapotranspiration (ET) to quantify consumptive water use, especially for irrigated agriculture to improve irrigation scheduling, and for estimating the volume of interstate water transfers, for example, in the Colorado River basin. [12][17][34][36][38]	Spatially consistent basin-wide monthly and annual maps of the distribution patterns of actual ET at ~30m resolution.	USBR-Water SMART Program, Western States incl: AK, AZ, CA, CO, MT, NM, TX, and WY	Near-term
Accurate estimates of riparian zone ET are needed to properly and soundly apportion river water for human and environmental needs [39]	Annual maps of ET from riparian vegetation for monitoring water use.	USBR	Near-term
Accurate estimates of ET for assessing rangeland health.	Monthly maps of ET for arid rangelands.	BLM, New Mexico State Engineer	Near-term
Monitoring evaporative losses over reservoirs and rivers	Monitoring evaporation / evapotranspiration losses over reservoirs and rivers	USACE, USBR	Medium-term
Identify illegally irrigated lands (D. Wegner, Review Board)	High-resolution estimates of evapotranspiration.	State Regulatory Bodies	Long-term

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Appendix A – Review Board

Name	Title and Organization
Michael Anderson	California State Climatologist
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Claudia Faunt	Research Scientist, United States Geological Survey
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Pat Lambert	Federal Liaison, Western States Water Council, USGS
Anke Mueller-Soljer	Program Manager, United States Geological Survey
John Nielsen-Gammon	Texas State Climatologist
Marty Ralph	Director, Center for Western Weather and Water Extremes (CW3E).
Mike Strobel	Director, National Water and Climate Center, United States Department of Agriculture
Brad Udall	Senior Water and Climate Scientist, Colorado State
Dave Wegner	Former Senior Staffer, United States House of Representatives, Water, Energy and Transportation Committees

Appendix B – Table of Needs Identified at 2014 Workshop

Western water managers were asked to identify their top three near-term needs where NASA capabilities can add value. Responses were received from state water managers in Alaska, Arizona, California, Colorado, Montana, Nevada, Texas, and Wyoming. Most of the respondents expressed interest in improved/ higher resolution evapotranspiration (ET) products or improved access to ET products. The need for snowpack quantification and observations, and improved groundwater monitoring were also of interest to most. A summary of responses organized by water supply, consumptive use, water infrastructure, and water quality are given the table below. Priority rankings are based on the number of states who identified that need. The top need in this case is for improved crop ET estimates

Category	Need	Priority
Water Supply and Availability	Snowpack quantification • Having an accurate read on snowpack volume for better estimates of runoff is vitally important to water managers responsible for making allocation decisions and forecasts. • Also important is evaluating the impact of environmental conditions (dust, pine mountain beetle, etc.) on snowpack.	2
	Precipitation forecasting • Sub-seasonal to seasonal precipitation forecasting is critical for strategic planning for water resources and flood potential. In the west, the need for S2S precipitation prediction is especially critical as it can inform reservoir operations decisions.	3
	Monitoring Groundwater • As aquifers are depleted, it is increasingly important to improve our ability to monitor groundwater supplies. • Subsidence as a result of drawing down aquifers can impact infrastructure and aquifers may lose capacity for recharge.	4
Consumptive Use	Evapotranspiration • Improved estimates of field-scale evapotranspiration (ET) to quantify consumptive water use, especially for irrigated agriculture to improve irrigation scheduling, and for estimating the volume of interstate water transfers, for example, in the Colorado River basin. • Improved access to ET estimates that would not require a team of experts to analyze or understand. • Soil moisture monitoring at high resolution.	1
Water Quality	• Assessment of ecosystem health (bays, estuaries, deltas, salinity, turbidity, suspended sediments, chlorophyll and algal blooms) • Assessment of water quality in reservoirs	6
Water Infrastructure Monitoring	• Aging water infrastructure and the possibility of catastrophic failure are also often brought up as concerns. NASA's Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) can be a valuable tool for monitoring and detecting compromised integrity of aqueducts, dams, and levee systems.	5

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