TITLE PAGE

Defining the rain-snow transition zone in the Northern Sierra Nevada

Application for:

WaterSMART: Applied Science Grants for Fiscal Year 2019

Funding Opportunity No. BOR-DO-19-F012

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1.1. Executive summary

Date: October 30, 2019

Applicant: Sierra Nevada Research Institute, University of California, Merced

City: Merced

County: Merced County

State: California

1.1.1 Project summary

The primary aim of this project is to develop an online system to provide accurate, real-time information on the size, distribution, and location of the rain-snow transition zone in the Northern Sierra Nevada. This system will incorporate data from two basin-scale wireless sensor networks, operational hydrologic data from California Data Exchange Center (CDEC), and radar-based snow-level data, and other historical and projected weather and climate data. It will report this rain-snow-transition information for use in two critical decision-support challenges for effective flood control. The first is timely information for scheduling reservoir releases to optimize storage, while providing capacity to accept storm runoff. The second is information to enable better coordination of releases from the multiple reservoirs in this portion of the Sacramento River basin, given the constraints of downstream flooding and environmental flows.

The project focuses on the American and Feather River basins (Figure 1), in which the California Department of Water Resources and other agencies have invested in on-the-ground distributed sensor networks that provide relevant data in unprecedented detail. Research using these data, the product of multi-million-dollar investments in instrumentation and analysis, has provided a proof of concept; and this project will develop a prototype operational system that can both inform flood-control decisions in these basins and later be scaled across other important headwater basins. This prototype system is being developed in two critical source-water river basins that are both high potential for flood risk and critical water supplies.

Recent large atmospheric-river, rain-on-snow, and more-intense runoff events have clearly demonstrated the immediate need for better real-time decision-support information that reflects on-the-ground conditions during storms.

The proposed applied science project involves moving demonstrated research tools into experimental operational use for estimating the rain-snow transition, in conjunction with ground-based radar and weather-forecast modeling. The work plan involves 5 main tasks with clear deliverables and milestones: 1) develop tools to provide real-time estimates of the rain-snow transition zone from available ground-based data, blended with other relevant data, 2) assess the ground-based rain-snow zone for historical storms in relation to values from ground-based radar and from weather-forecast modeling, and report apparent relationships, 3) provide tools to report historical and real-time information of snowpack, soil-water storage, and runoff potential from ground sensors, together with other relevant data sources, 4) build a data-management and delivery system for these data, including a user dashboard, in consultation with data users, and 5) outline a plan for improving and scaling this integrated approach to other headwater basins, including measurement, operations, maintenance, and user demand for information for various decision-support systems.

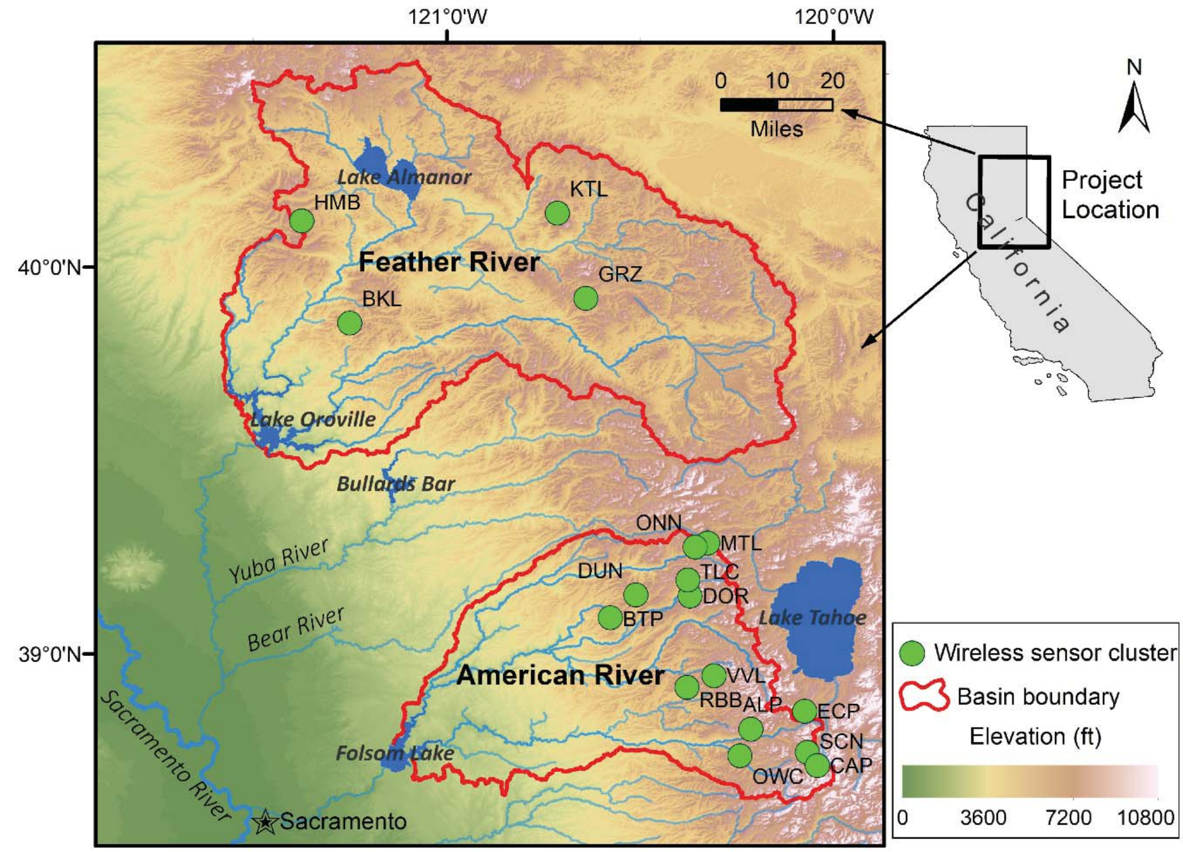

Figure 1. Map showing the American and Feather River basins and two basin-scale wireless sensor networks.

The Sierra Nevada Research Institute (SNRI) at the University of California (UC), Merced, in collaboration with the California Department of Water Resources (DWR), is requesting $300,000 from the U.S. Bureau of Reclamation (USBR) to support the continued development and application of this new technology to provide more accurate and reliable rain-snow transition zone in areas of common interest to DWR and USBR. Matching will be provided by DWR. The project will be carried out by the SNRI and DWR. The SNRI will also collaborate with our UC Water Security and Sustainability Research Initiative (UC Water), which links together multiple campuses with over 50 researchers working on California's water information, institutions, and infrastructure.

1.1.2. Length of time and estimated completion date for project

The proposed project will take 3 years and can be finalized by the end of 2022, assuming it is initiated in January 2020.

1.1.3. Federal facility information

The headwaters of both watersheds include significant fractions of National Forest land, for example, 64% of the 2.2 million acres in the Upper Feather River watershed are Federal (primarily National Forest). The American River Watershed forms a drainage basin of approximately 2140 square miles (1.3 million acres) above Folsom Reservoir, the main impoundment on the American River. Folsom Reservoir is part of Reclamation's Central Valley Project (CVP). Flood control on both the American and Feather River basins is based on a release schedule in consultation with the U.S. Army Corps of Engineers (USACE). Approximately 78 miles from Sierra Valley to Lake Oroville on the Middle Fork of the Feather River are federally designated wild and scenic river.

1.2. Background information

The climate-change narrative includes the concept of more rain and less snow in mountain areas of California. Knowing the rain-snow transition zone during storms is essential for forecasting the amount and timing of runoff, which has significant impacts on flood management and water supply. As climate-change impacts continue to mount, knowledge of the size, distribution, and location of the rain-snow transition zone will play a key role in deciding which adaptation strategy is relevant for deployment and when alternate actions need to be considered. Historical instrumentation lacks sufficient spatial coverage to provide information on the time and space evolution of the rain-snow transition during storms.

Recent research suggests that the size, distribution, and location of the rain-snow transition zone can be measured (Cui et al., 2019a; Zhang et al., 2017a). Research deployments of wireless sensor networks, plus radar and other data, provide this information and can be further developed to offer a blended product that can be applied across in the mountain basins in the northern Sierra Nevada, and more broadly. This would have direct benefits to flood-management response and water-supply reliability, as well as begin critical documentation of the already changing balance of rain and snow, providing key information supporting climate resiliency.

The overarching goal of the proposed project is to develop an online system with the hydrologically important rain-snow transition zone, for supporting decision making. The broader goal of the project is to advance the knowledge of the rain-snow transition zone for real-time forecasting, which in turn contributes to optimizing flood management, improving cooperation between reservoirs, promoting forecast-based reservoir operations and management, and benefiting the water supply reliability.

1.2.1. Flood control in Feather and American River basins

The American and Feather River basins are on the western slope of the Sierra Nevada, contributing significant flows to the Sacramento River and Delta. On average, about 44% of the annual flow in the Sacramento River is from the Feather River (USACE, 2015). The Feather River basin has an area of 3640 square miles above the lowermost Oroville Dam. Through the State Water Project (SWP), the Lake Oroville on the Feather River provides up to about 3 million acre-feet per year on average to municipal and agricultural water users in the Central Valley and the coastal areas. The American River basin has an area of 1850 square miles above the Folsom Dam. The Folsom Reservoir provides 500,000 acre-feet of water per year for irrigation, municipal, and industrial uses.

The dams and reservoirs on the two rivers are important components in the flood protection for the Sacramento areas (CRS, 2006; USBR, 2003). Flooding is frequent and natural in the American and Feather River basins, due in part to its Mediterranean climate and geography. The winter and spring rainfall delivered by the warm and wet west-coast storm patterns, as well as rainfall combined with snowmelt, are the major reasons that have resulted in historical floods (Cowin & Bardini, 2011). These floods have caused significant damage to the Sacramento areas. By storing inflows from floodwaters and controlling the water release, dams and reservoirs at the Lake Oroville and Folsom Lake are operated to reduce the damaging flood peaks. Many agencies, such as the USBR, DWR, Sacramento Area Flood Control Agency (SAFCA), and USACE, have a role in operating the flood control facilities.

For Lake Oroville on the Feather River (Figure 2a), during the winter storm season (November to April), up to 3.2 million acre-feet of storage is allowable to reserve space for flood storage (USBR, 2003). Its flood control is based on a release schedule and in consultation with the USACE. After April, its storage limit increases as the need for flood storage reduces. The Oroville Dam is located at the outlet of the Feather River basin and upstream from the Yuba and Bear tributaries. The Bullards Bar Reservoir, on the North Fork of the Yuba River, has a maximum storage of 969,600 acre-feet. However, only a third of the streamflow in the Yuba basin is regulated by the Bullards Bar Reservoir, due to the lack of major flood control dams on the Middle and South Forks of the Yuba River. As such, the Lake Oroville and Bullards Bar Reservoir are cooperatively operated and managed, in order to control the flood potential at the confluence of the Yuba and Feather Rivers. During flood or storm periods, the operators at the two reservoirs have timely cooperation by sharing forecasting information and operational schedule. Note that the Yuba river is not part of this project, as it does not yet have an on-the-ground sensor network like that in the Feather or American.

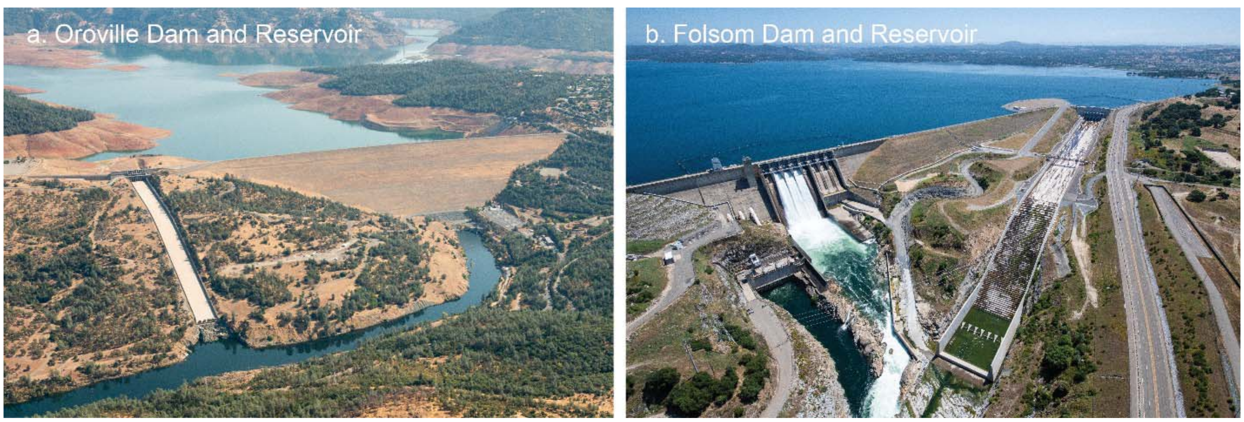

Figure 2. a) The northeast view of Oroville Dam and Reservoir on the Feather River, and b) the aerial view of Folsom Dam and Reservoir on the American River. Sources: Florence Low, California Department of Water Resources, https://pixel-ca-dwr.photoshelter.com**.**

For the American River (Figure 2b), the Folsom Dam and Folsom Reservoir are located at the confluence of the three forks, providing flood protection, hydroelectricity, irrigation and municipal water use, and water supply for ecosystem function. Folsom Lake has a total storage of 977,000 acre-feet. The floodwaters can be safely released by its spillway with maximum design release of 115,000 cubic feet per second. Folsom Reservoir is the main reservoir operating for flood control on the American River, since the upstream reservoirs (e.g. French Meadows, Hell Hole, and Union Valley) have not have explicit flood-control requirements.

The coordination and integrated management between facility operators are important since California's water supply and flood-control facilities are physically interconnected. During a flood event, the DWR cooperates with the National Weather Service (NWS) and many other federal, state, and local agencies, such as the USBR, USACE, SWP, SAFCA, the California Governor's Office of Emergency Services, the California Department of Forestry and Fire Protection, and Yuba water agency (DWR, 2018). These agencies work closely to make coordinated reservoir release decisions. The hydrologic forecast information (e.g. river, flood, and precipitation forecasts) is provided and updated by the NWS using hydrologic models. For the SWP facilities including the Lake Oroville on the Feather River, the SWP coordinates the reservoir operations and briefing and planning activities. For many USBR reservoirs including the Folsom Dam on the American River, the CVP coordinates the reservoir operations and briefing and planning activities. The DWR developed an online GIS system, named Flood Emergency Response Information Exchange (FERIX, http://ferix.water.ca.gov), providing real-time data collection, flood information, hydrologic and hydraulic models, and decision support. The FERIX allows the cooperating agencies to access and exchange information, improving flood emergency preparedness and response. A flood alert or flood mobilization may be issued by the DWR, according to the severity of the forecasted or actual flooding.

Runoff forecasts from hydrologic models are important for forecast-informed reservoir operations. The on-the-ground rain-snow transition zone is key information in the hydrologic modeling. In general, precipitation within the rain-snow transition zone is a mix of rain and snow during storms, and precipitation in the phase of snow above the zone, and rain below the zone. There is a general consensus that the higher of the rain-snow transition zone at the beginning of heavy precipitation, the greater the possibility of the occurrence of floods from rapid runoff (Fletcher, 1940). Other factors, such as the intensity and duration of the precipitation and on-the-ground snow depth and density, affect runoff generation, since the melted snow from a rain-on-snow event contributes a portion of runoff. It is currently difficult to determine the quantity of runoff originated from melting snow, or from a combination of rain and melted snow during storms. To infer the on-the-ground rain-snow transition zone, Frequency-Modulated Continuous Wave (FMCW) radars were deployed in the Sierra Nevada, to estimate the atmospheric snow level by identifying the elevation of the maximum reflectivity in a bright band (White et al., 2010). Besides the single elevation of the snow level from radar, information on the size and timing of the on-the-ground rain-snow transition zone is also important. These additional attributes are not measured or inferred from the radars. With advanced information on the rain-snow transition zone, flood modeling and estimates of the runoff-contributing area could be significantly improved.

Climate variability can result in changing the ratio of rain to snow and a shift in the timing of runoff, adding greater stress to water-supply reliability. In recent decades rising temperatures have caused precipitation to occur as more rain and less snow, with snowpack melting earlier, and earlier runoff in the Sierra Nevada (USBR, 2014). Since reservoir operations are developed based on the historical record of the timing of snowpack accumulation and melt, these hydrologic changes would significantly impact the integrated water management through reservoir operations (Anderson, 2016). The temperatures in the Sierra Nevada are projected to increase steadily, with changing about 3 °C by the late 21st century (USBR, 2016). Implementing adaptive flood rule in reservoir operations is a viable adaptation strategy worth pursuing, due to the anticipated earlier runoff refilling reservoirs earlier.

Atmospheric rivers are currently drawing the attention of the DWR and others since they transport enormous amounts of moisture, which can lead to copious precipitation, enhanced runoff, and flooding (Anderson, 2016). The atmospheric rivers are long and narrow corridors of water-vapor flux in the lower troposphere, and located in the warm sector of extratropical cyclones, and often landfall over California and the broader west coast of the United States. For California, up to 50% of annual precipitation and 40% of the snowpack can be contributed by atmospheric rivers (Dettinger, 2016). In water year 2017, atmospheric rivers landfall over California for 67 days, which is triple the climatological average for the last 20 years (White et al., 2019). With climate warming potentially resulting in more rain-on-snow events from projections of more-intense atmospheric river events, it is critical to understand how the rain-snow transition zone evolves during the atmospheric-river events.

1.2.2. Technology advances

Recently, two basin-scale wireless sensor networks in the American and Feather River basins have been developed to reliably and cost-effectively provide important hydrologic measurements in real time (Figure 1 above; Malek et al., 2017, 2019; Welch et al., 2013; Zhang et al., 2017b). The American network was initiated by the DWR under the California Natural Resources Agency, Sierra Nevada Adaptive Management Program, and expanded with a $2 million grant from the National Science Foundation. The Feather network was developed as a partnership between the DWR, Pacific Gas and Electric Company, and the California Energy Commission through the Electric Program Investment Charge (EPIC) program.

The two basin-scale wireless sensor networks consist of a total of 17 spatially distributed clusters. Specifically, for the American River basin, 13 sensor clusters were deployed in the elevation range of 4950-8930 ft, covering the main snowmelt-producing parts of the basin. The 4 clusters in the Feather River basin were deployed across a 5570-7470 ft range in elevation, which includes 1370 square mile (76%) of the basin. Each of these clusters contains more than 10 sensor nodes, which are wirelessly physiographically connected with a base station and repeater nodes (see the Alpha site in the American River basin in Figure 3, as an example). The sensor nodes within a cluster are located at representative locations spanning across areas of approximately 250 acres, recording snow depth, air temperature, relative

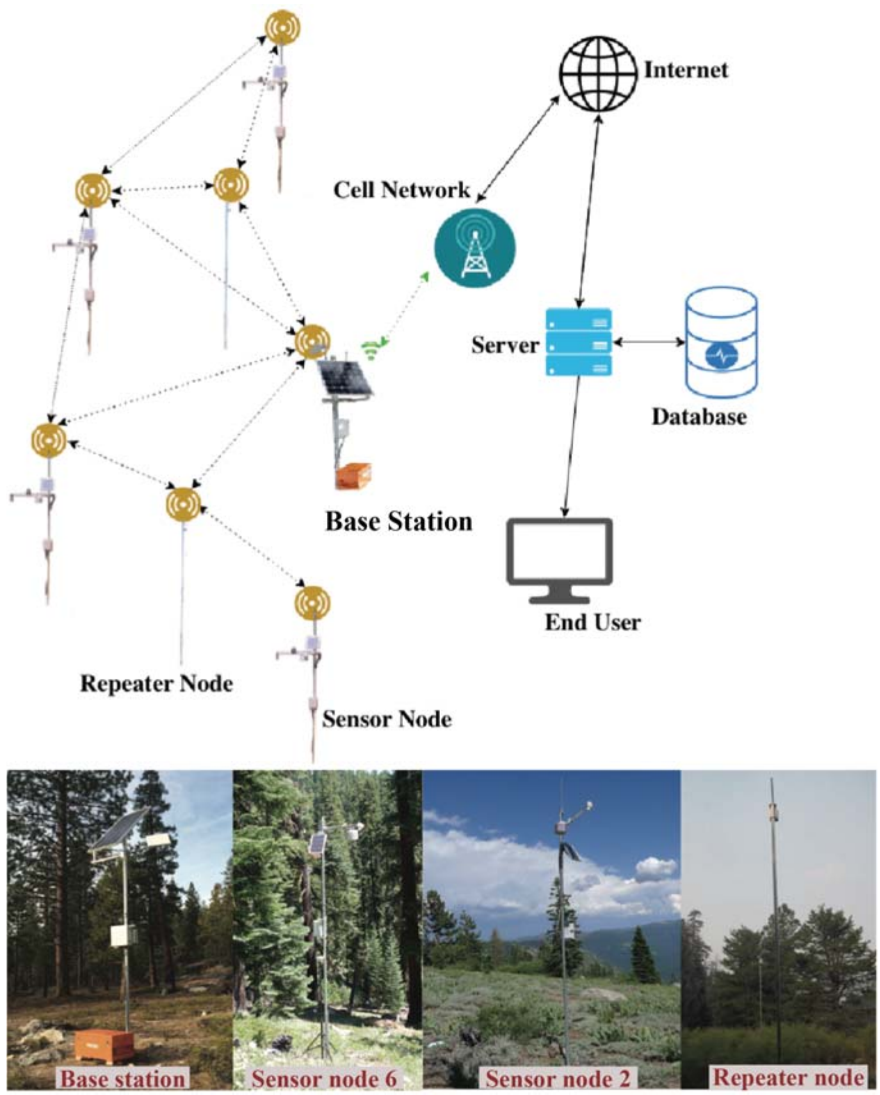

Figure 3. System architecture and photos of a wireless-sensor cluster at the Alpha (ALP, 7440 ft elevation) in the American River basin. From Malek et al. (2019) and Zhang et al. (2017a).

humidity, soil moisture, and solar radiation. With the basin-scale distributed clusters deployed across a wide elevational range in mixed rain-snow mountainous areas, the two observatory networks capture the spatial variability of measurements associated with elevation, aspect, slope, and canopy cover. For example, the across-cluster and within-cluster heterogeneity of snow-depth measurements can be clearly captured by the sensor network (Figure 4).

The two wireless sensor networks provide valuable, spatially representative hydrologic measurements, which are not available from operational stations. These wireless sensor data have been used to improve snow water equivalent and runoff estimates (Malek et al., 2019; Zheng et al., 2018), showing apparent advantages compared with relatively sparse traditional operational data. With the dense data with wide spatial coverage, the rain-snow transition zone was investigated by proposing a reliable method based on dew-point temperature (Cui et al., 2019a; Zhang et al., 2017a), which was evaluated by on-the-ground snow accumulation and ablation. Meanwhile, mountain precipitation amounts and pattern could be further reliably estimated using the wireless sensor data (Cui et al., 2019b; Zhang et al., 2017a), since precipitation data from relatively sparse gauges in high-elevation, snow-dominated areas are subject to significant uncertainty due to the wind-induced undercatch. These research activities on the basin-scale wireless sensor networks have contributed to obtaining better hydrologic information in the American and Feather River basins.

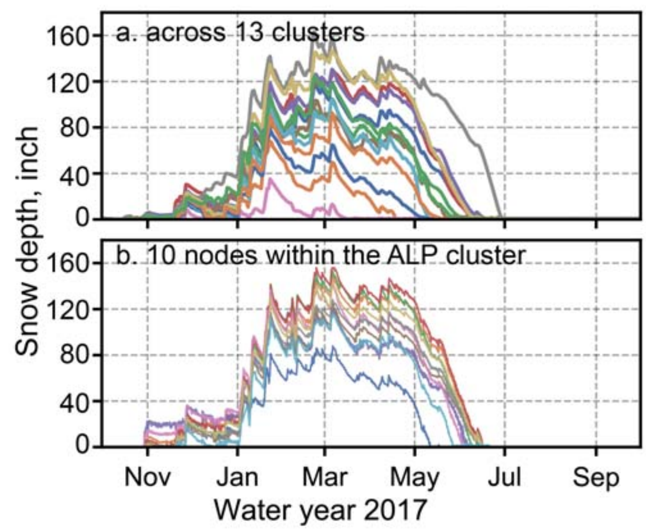

Figure 4. The across-cluster and within-cluster heterogeneity of snow-depth measurements captured by the basin-scale wireless-sensor network in the American River basin.

1.3. Project location

The project is located in two mountain basins in the Northern Sierra Nevada of California, i.e. the American River basin and the Feather River basin (Figure 1 above). The two basin-scale wireless sensor networks contain 17 sensor clusters in total, 13 of which are distributed across the American River basin, and the remaining 4 clusters are in the Feather River basin. The shapefile of the geographic location of the project is attached in Appendix B.

The Category-B applicant Sierra Nevada Research Institute at the University of California, Merced campus conducts basic and applied research in the Sierra Nevada and the San Joaquin Valley regions of California. The SNRI has established strong interactions with related research units within the UC system (e.g. through UC Water) and close collaborative relations with local, state, and federal agencies. The data and research results from the SNRI are shared with agency decision makers and with public and private stakeholders. For this proposed project, the SNRI will collaborate with DWR and its multiple partner agencies across the project area. The SNRI has a successful history of partnering with the DWR in the past, that initiated and developed the two basin-scale wireless sensor networks in the American and Feather River basins. The DWR will participate in the project and provide support for this project. The SNRI and DWR continue to have this working opportunity to improve flood management and leverage water supply. The partner, the Department of Water Resources, has provided a letter of support (Appendix A in the Section of ATTACHMENTS).

1.4. Technical project description and milestones

The project consists of five main tasks:

1. Develop tools to provide real-time estimates of the rain-snow transition zone from available ground-based data, blended with other relevant data.
2. Assess ground-based rain-snow elevations for historical storms in relation to values from ground-based radar and from weather-forecast modeling, and report apparent relationships.
3. Provide tools to report historical and real-time snowpack and runoff potential from ground sensors, together with other relevant data sources.
4. Build a data-management and delivery system for these data, including a user dashboard, in consultation with data users.
5. Outline a plan for improving and scaling this integrated approach to other headwater basins, including measurement, operations, maintenance, and user demand for information for various decision-support systems.

1.4.1. Develop rain-snow transition zone

We will incorporate methods for identifying the rain-snow transition zone into real-time data-processing tools. The approach is based on a published and tested model using the dew-point temperature (T_{dew}) derived from the wireless sensor networks (Cui et al., 2019a; Zhang et al., 2017a). We will further identify the rain-snow transition zone using co-located high-spatial-resolution snow information (i.e. accumulation and ablation) from the wireless-sensor networks (for example, Figure 5). We will also blend operational CDEC data in order to cover the full range from all rain to all snow, with emphasis on mixed-rain-snow events.

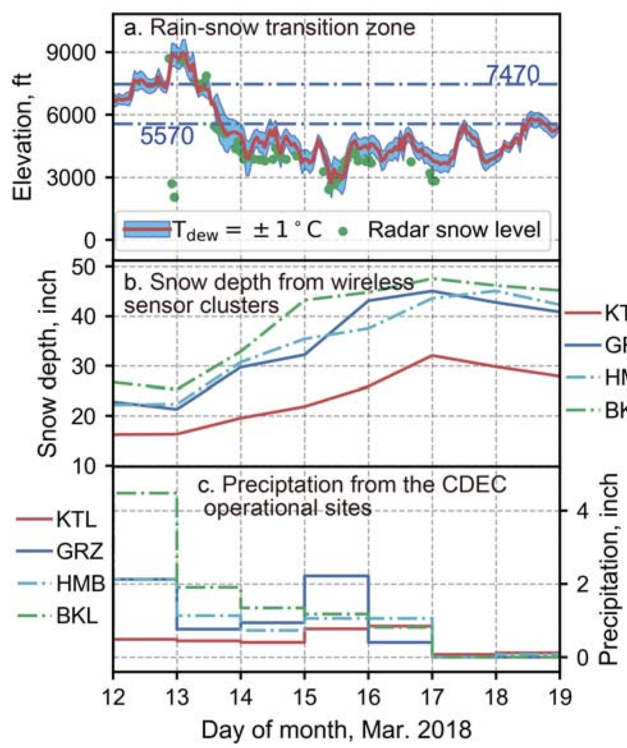

Figure 5. Rain-snow transition zone (blue band in top panel a) in the Feather River basin measured by the four wireless sensor clusters during a cold storm in March 2018.

A conceptual model describes the evolution of the rain-snow transition zone during a storm. As the elevation of rain-snow transition zone changes with different types of winter storms, the precipitation phase across the basin varies. Since snow can stay on the mountain surface and melts slowly, the storms with low elevation of rain-snow transition zone often have low runoff potential, which poses little threat to the flood management and reservoir operation. However, the warm storms and atmospheric-river storms are often associated with higher elevation of rain-snow transition zone, which leads to a larger contribution area of runoff. Particularly during atmospheric-river storms, heavy precipitation, plus the significant rain-on-snow melted snow in low-elevation areas, will result in the substantially augmented runoff, threatening the flood management, reservoir operation, water supply, and water delivery. In the proposed project, we will further develop the conceptual model (for example, Figure 6 as a starting point), to provide potential guidance for flood forecasting and reservoir operation.

The main data will come from two sources, the wireless-sensor networks and CDEC. At this point, the systems are only partially integrated, and DWR will continue working to further integrate these.

Wireless sensor networks. The 15-min-interval data will come from two basin-scale wireless-sensor networks, in the American and Feather River basins. The two wireless-sensor networks consist of 17 spatially distributed clusters, with a total of 178 sensor nodes, providing dense measurements of air temperature, relative humidity, snow depth, soil moisture, and solar radiation (Malek et al., 2017, 2019; Zhang et al., 2017a). As the two wireless-sensor networks capture the spatial variability of measurements associated with elevation, aspect, slope, and canopy cover across the basins, the rain-snow transition zone can be measured or derived based on these dense measurements. Limited real-time data are available online, as these have been research rather than operational networks (http://glaser.berkeley.edu/wsn/).

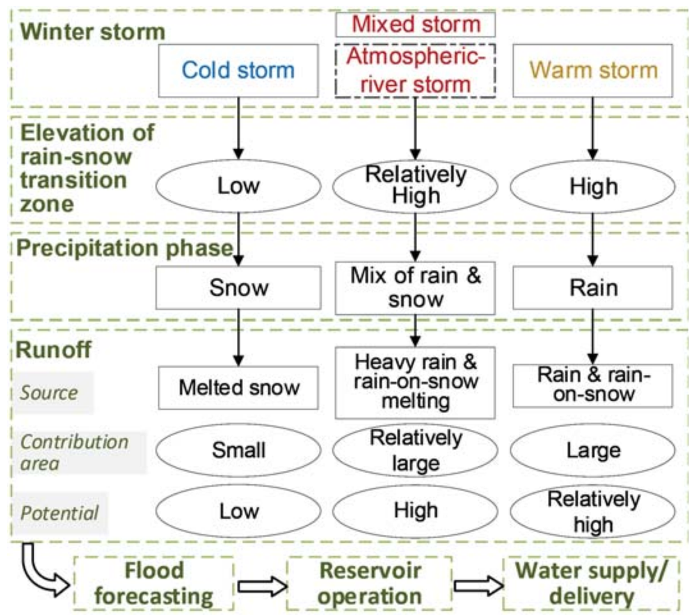

Figure 6. Rain-snow transition zone in different storms (particularly, the important atmospheric-river storm) and its impacts on runoff and decision support system.

California Data Exchange Center (CDEC). The CDEC database (http://cdec.water.ca.gov) is publicly available via the internet, providing the extensive real-time hydrologic information gathered by various cooperators throughout the state (DWR, 2018). The CDEC operates a data exchange via network connections between various federal, state agencies, and other public agencies. The CDEC collects real-time data, including precipitation, snow water content, temperature, weather data, river stages, and water quality, to support the flood forecasts, water supply forecasts, and schedule reservoir releases. The CDEC historical and real-time data, related to precipitation, snow, temperature, and weather data in the American and Feather River basins, will be quality controlled and then incorporated in the project.

1.4.2. Assess estimates across data sources

Operationally, weather-forecast models provide estimates of the freezing elevation, which is an indication of the expected rain-snow transition zone on the ground. These data can be evaluated directly and potentially adjusted using upward-looking radar data. The potential relationships in the transition zone across different sources will be investigated. In addition, historical and climate-projection gridded data will be used to investigate the characteristics of the rain-snow transition zone, including its location, distribution, and thickness (see the example in Figure 7), in historical periods and future climate scenarios, particularly during atmospheric river events.

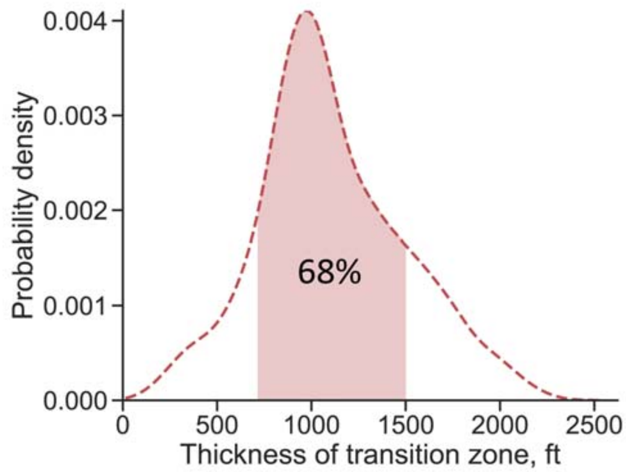

Figure 7. Probability density of thickness of the rain-snow transition zone in the Feather River basin for water years 2017-18. About 68% of the rain-snow transition zones have the thickness between 700 and 1500 ft.

Radar data: The atmospheric snow level is observed by the FMCW radars by identifying the elevation of the maximum bright-band reflectivity (White et al., 2010). The atmospheric snow level data are included in the project for comparison and investigation of the on-the-ground rain-snow transition elevation. We will retrieve the atmospheric snow level at nearby sites (e.g. the Colfax 39.080° N, 120.938° W, 2110 ft elevation, and the Oroville 39.532° N, 121.488° W, 374 ft elevation) around the American and Feather River basins from the Earth Systems Research Laboratory (ESRL, http://www.esrl.noaa.gov).

Weather forecast data: The river and flood forecasts from the National Weather Service (NWS) Hydrologic Services Program are used by DWR during flood emergencies (DWR, 2018). The forecast data about precipitation and temperature from the NWS (https://www.weather.gov) will be incorporated in this project, to allow us to develop a forecasting tool of the rain-snow transition zone, and corresponding runoff-contribution areas during storms.

Historical gridded data: The gridded climate data Parameter-elevation Relationships on Independent Slopes Model (PRISM, http://www.prism.oregonstate.edu/) product is interpolated based on ground climate observations from a wide range of monitoring networks. The PRISM dataset will be incorporated in this project, to help investigate the historical distribution and variation of the rain-snow transition zone. Another atmospheric reanalysis data from NASA, called Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2, https://gmao.gsfc.nasa.gov) will be also included to investigate the representativeness of on-the-ground rain-snow transition zone in the atmospheric modeling data, such as the 0 °C isotherm, and to identify the atmospheric river.

Climate projections: Multi-model climate projections in 3-hourly temporal resolution from the latest Coupled Model Intercomparison Project Phase 6 (CMIP6, https://www.wcrp-climate.org/) will be collected. The relevant temperature, precipitation, and other atmospheric variables from climate projections will be used to investigate the characteristics of the rain-snow transition zone in future climate warming scenarios. As previous reports have shown (Cowin & Bardini, 2011; USACE, 2015; USBR, 2014, 2016), flood control, water supplies, and demands will be impacted by the potential climate change, due to more intense and frequent extreme events, and the combination of earlier snowmelt and shifts of precipitation phase from snow to rain. The analysis of the rain-snow transition zone using climate scenarios supports climate-resiliency efforts and contributes to a better understanding of the runoff-contributing area, as well as its major implications for water supply, flooding, and reservoir operation.

1.4.3. Report historical and real-time snowpack and runoff potential

For runoff forecasting, the information of on-the-ground snowpack, soil moisture, and rain-snow transition zone is crucial, since the rain-on-snow melted snow can contribute a portion of runoff, particularly with high ground antecedent moisture and heavy precipitation events with relatively high transition zones, which are often associated with atmospheric rivers.

For the on-the-ground snowpack information, gridded snow-depth and snow water equivalent (SWE) maps can be produced by blending the wireless sensor data with historical SWE images, following the methods developed by Zheng et al. (2018) in our previous studies. Sensor-network data will come from the same sensor nodes, as for the rain-snow transition zone. The gridded snow products from the sensor network will be compared to the reference data, which will come from MODIS-based SWE maps (e.g. Schneider & Molotch, 2016) and when available, historical (or current) NASA's Airborne Snow Observatory (ASO) data (https://aso.jpl.nasa.gov/). These snow maps will provide key inputs for rain-on-snow assessment. Zheng et al. (2018) has previously shown that this approach can reproduce ASO LiDAR data (Figure 8).

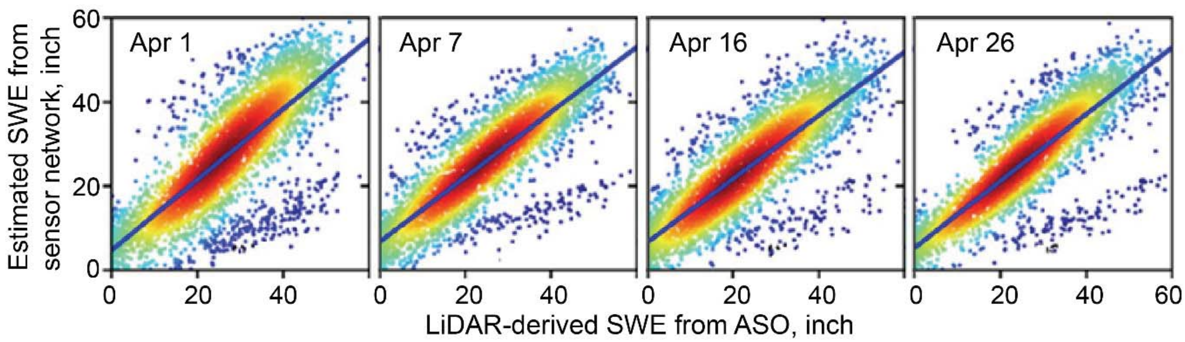

Figure 8. Estimated snow water equivalent (SWE) from the wireless network versus LiDAR-derived SWE from ASO on four days during the peak season in water year 2016.

With the information on the location and size of the rain-snow transition zone from the wireless sensor networks, the runoff-contributing area during storms can be determined. Most damaging floods in the Northern Sierra Nevada of California have occurred when rain falls on snow-covered areas, during atmospheric-river storms and warm storms (Kattelmann, 1997; Lundquist et al., 2008). A substantially greater runoff-contributing area is typical in these storms, while not quantitatively evaluated before, due to the lack of accurate information of rain-snow transition zone. Advanced knowledge of the rain-snow transition zone in this project will enable us to investigate and forecast the runoff-contributing area, together with information on snow cover and topography characteristics of the mountain basin (Figure 9 as a starting point). In particular, the runoff-contributing area during the atmospheric-river storms would be specifically investigated in the proposed project, due to their significant impacts on flood control and water supply.

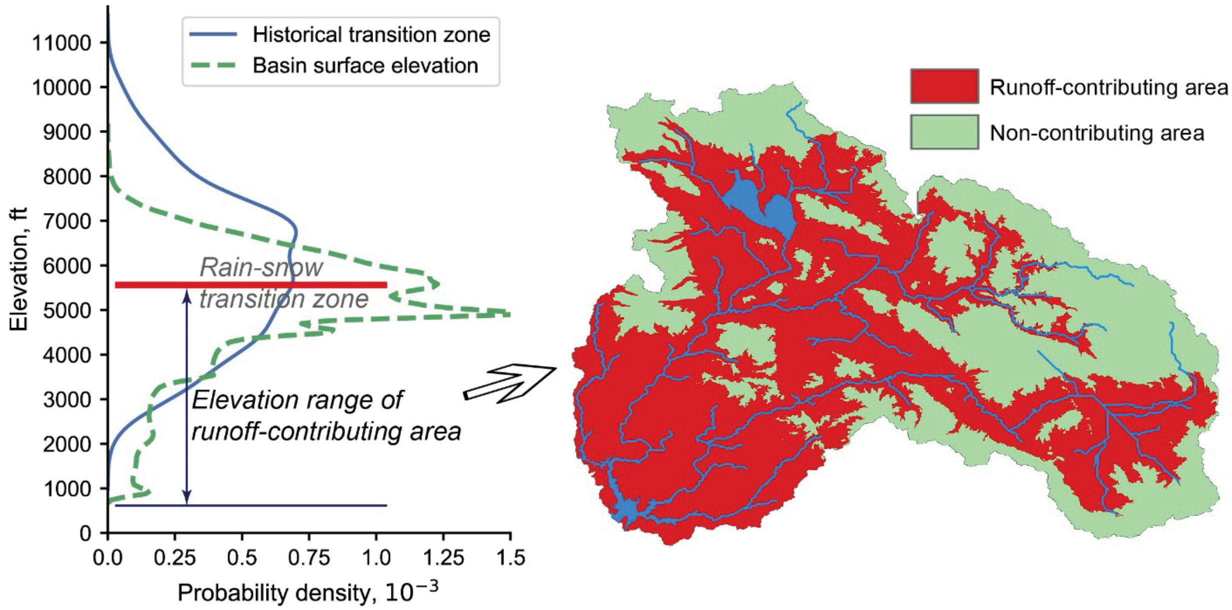

Figure 9. Runoff-contributing area for a rain-snow transition zone at 5600 ft elevation in the Feather River basin.

1.4.4. Build the Dashboard

The dashboard is the online tool that will display the measured and forecasted data from the wireless sensor clusters, CDEC, and other sources, for the use by local, regional, state and federal agencies. All data will be stored and organized in a data-management system, which is connected to the dashboard. Beside the visualization of real-time data from the wireless sensor clusters, interpolated snow map, the webserver would be deployed with a Python-based program that will measure and forecast the rain-snow transition zone using the wireless sensor networks, CDEC data, and NWS data, based on the above investigations and explorations of transition zone using various data sources. After obtaining the information of the rain-snow transition zone, the predicted runoff-contributing area for the American and Feather River basins will be displayed in a web map on the dashboard. The data on the dashboard will be updated several times per day using telemetry, data platform services, and the Python-based program.

The dashboard is designed and developed as a decision support system, providing a simple graphic overview of the real-time observed data and forecasted data. The dashboard allows the users to easily access the project data, which helps decision making about flood management and reservoir operation. The dashboard will be refined with inputs from a stakeholder working group to ensure that its web application and user interface support the agency's information needs.

1.4.5. Outline long-term plan

The prototype system in the project includes real-time wireless sensor data and snow maps, a program to measure and forecast rain-snow transition zone and runoff-contributing area, and an online dashboard to provide real-time decision support for the stakeholder and other interested users. As the project focuses on the northern Sierra Nevada, i.e. the Feather and American River basins, the developed prototype system will be evaluated in real applications during storms or floods, regarding its performance on the accuracy and informativity. The hydrologic information from the prototype system can be used as complementary to the DWR's FERIX system.

The prototype system will be documented about its utility on how to use its hydrologic information to support decision making. A report on its application for real-time forecasting and operations in the Feather and American River basins will be developed. More broadly, the project will propose a long-term plan for improving and scaling this prototype system to other headwater basins in the Sierra Nevada of California, including measurement, operations, maintenance, and user demand for information for various decision-support systems.

1.4.6. Project schedule and milestones

The major tasks, milestones, and implementation schedule of the proposed 3-year project (Jan 2020 - Dec 2022) are shown in Table 1.

Table 1. Schedule for project tasks and milestones for 2020-2022.

Major Tasks	Milestones	Timeline
Develop rain-snow transition zone	Real-time data-processing tool to identify the rain-snow transition zone Conceptual model describing the evolution of the transition zone	Jan 2020 - May 2020
Assess estimates across data sources	Forecasting program for the rain-snow transition zone Report apparent relationships of the transition zone from ground sensors and weather-forecast modeling Characteristics of the transition zone in atmospheric-river events and future climate scenarios	Jun 2020 - Dec 2020
Report historical and real-time snowpack and runoff potential	Tool to generate real-time snow maps Program to identify and forecast the runoff-contributing area	Jan 2021 - May 2021
Build Dashboard	Inputs from a stakeholder working group Database of the measured and generated data Web application dashboard	Jan 2021 - May 2022
Outline long-term plan	Report of the prototype system and the plan for scaling to other headwater basins	Jun 2022 - Dec 2022

1.5. Data management

The project will employ a data management system to store, organize, and share the collections of all data mentioned above. For that purpose, the open-source data management system Clowder may be used (https://github.com/clowder-framework/clowder), as it is customizable, scalable, and well maintained. The data management system will be deployed in a GNU/Linux server. The processed and produced data from this project would include text, spreadsheets, binary file, image, geospatial data, program/software, and documentation. All data will be stored in commonly used and preservable formats, wherever possible. For example, spatially explicit data will be stored in the format of GeoTiff, which is a standard image file format for Geographic Information System (GIS) applications. By following a metadata standard, each of the datasets will include appropriate metadata, describing the location of data collection, methods, and other key information. Then all data will be uploaded and ingested to the data management system using a web front end. As such, the data are conveniently and user-friendly shared with collaborators, stakeholders, and interested users through the web service.

An online dashboard will be developed in this project to deliver important visualized data for supporting the decision-making by local, regional, state, and federal agencies. The dashboard will be deployed in the GNU/Linux server and connected to the data management system, such that the real-time and forecasting data will be reported and displayed through this interactive web dashboard.

1.6. Evaluation criteria

Evaluation Criterion A — Benefits to Water Supply Reliability

A1. Describe the water management issue(s) that your project will address.

The Lake Oroville on the Feather River and Folsom Reservoir on the American River are important components of State Water Project (SWP) and Central Valley Project (CVP), providing flood protection and water supply for the Central Valley and other areas in California. The changing of rain versus snow in the Sierra Nevada mountains and heavy precipitation associated with atmospheric rivers are adding greater stress to flood control and water supply reliability in the two basins and surrounding Sacramento areas. Real-time forecasting hydrologic information (e.g. the rain-snow transition zone and ground snowpack) is crucial and needed for supporting the decision making of reservoir operation, flood management, and water supply.

A2. Explain how your project will address the water management issues identified in your response to the preceding bullet.

The project will develop a prototype system that incorporates data from various sources, particularly the high-resolution spatiotemporal data from the two basin-scale wireless sensor networks, to provide real-time forecasting rain-snow transition zone, runoff-contributing area, and snowpack in the basins. An online dashboard will be developed to interactively and easily deliver and display the important data for the uses by local, regional, state, and federal agencies. The real-time and forecast hydrologic information, e.g. the rain-snow transition zone, is crucial for supporting the decision making in reservoir operation and cooperation between the reservoirs in the Northern Sierra Nevada, which in turn significantly impact the flood response, water supply reliability, and water deliveries in the SWP and CVP, particularly for the Sacramento areas.

A3. Describe to what extent your project will benefit one of the water management objectives listed in the preceding bullets.

The real-time and forecasting of hydrologic information from the dashboard are valuable information for reservoir operators and decision-makers involved in a flood emergency during storms, and in balancing water supply objectives. Besides the web dashboard and data management system, a better understanding of the rain-snow transition zone would be provided by investigating the transition zone in the historical, real-time, short-term forecasting, and future climate warming perspectives. In particular, the hydrologic information during the atmospheric-river and rain-on-snow events will be given more attention. From a climate change perspective, knowing the rain-snow transition zone in future climate scenarios is helpful to support water-supply reliability and update reservoir operations built on historical hydrologic information.

A4. Explain how your project complements other similar applicable to the area where the project is located.

We are not aware of any related ongoing projects about real-time forecasting of the rain-snow transition zone in the American and Feather River basins using this sort of distributed measurements. In particular, the high spatial and temporal resolution data from the basin-scale wireless sensor networks are valuable and unique in the proposed project. The DWR currently uses the information from the CDEC and FERIX, which does not contain the hydrologically important rain-snow transition zone. As complementary, the project will provide an interactive web dashboard to display these important real-time forecasting of the on-the-ground transition zone, runoff-contributing areas, and snowpack.

Evaluation Criterion B — Need for Project and Applicability of Project Results

B1. Does your project meet an existing need identified by a water resource manager(s) within the 17 Western States?

The project meets the need of the California Department of Water Resources (DWR), which provides technical support to agencies across the state. The Category B applicant SNRI will work closely with the DWR during the project. The project activities will address the needs from the DWR, accordingly, since the DWR will participate in the project and provide support. A letter of support from the DWR is attached in Appendix A.

B2. Will the project result in an applied science tool(s) or information that is readily applicable, and highly likely to be used by water resource managers in the West?

The prototype system, including the online dashboard and data management system, will be publicly accessible by the DWR and other local, regional, state and federal agencies. The information provided by the prototype system would be readily applicable for informing the management and coordination through the DWR. As one of the major tasks in the project, we will document the utility of the prototype system and report its application for real-time forecasting and operations in the Feather and American River basins. The plan for improving and scaling this prototype system to other headwater basins, including measurement, operations, maintenance, and user demand for information for various decision-support systems, will be proposed in the project.

Evaluation Criterion C — Project Implementation

C1. Describe the objectives of the project and the methodology and approach that will be undertaken. Provide support for your methodology and approach.

The objective, methodology, tasks, and approach of the project are described in Section 1.4 of Technical project description and milestones. There are five inter-related tasks to move the information system from research to operations.

C2. Describe the work plan for the project. Include an estimated project schedule that shows the stages and duration of the proposed work, including major tasks, milestones, and dates.

The project is anticipated to be completed in 3 years and its major tasks, milestones, and dates are shown in Table 1 above.

C3. Describe the availability and quality of existing data and models applicable to the project.

The data and models in the project are described in Section 1.4 of Technical project description and milestones above.

C4. Identify staff with appropriate credentials and experience and describe their qualifications.

The project team members have developed and deployed the wireless-sensor networks, and conducted studies about rain-snow transition zone, snowpack, and runoff, using the data from the networks in the American and Feather River basins (Cui et al., 2019a; Malek et al., 2019; Zhang et al., 2017a; Zheng et al., 2018). At this point, these data are partially integrated with other data sources, such as the CDEC (http://cdec.water.ca.gov/dynamicapp/staMeta?station_id=BTP). The wireless-sensor data were previously stored in an InfluxDB database and visualized via a Grafana web frontend (Malek et al., 2017). Considering our previous activities, the project team has sufficient experience and skills to develop the prototype system mentioned above. In addition, researchers affiliated with UC Water can provide collaboration with the project team. Thus, upon approval of the project, the team will be ready to immediately implement all the activities.

C5. Provide a summary description of the products that are anticipated to result from the project.

The products for the project includes, a) an online dashboard displaying the rain-snow transition zone and other data from a data management system; b) a report on the prototype system and its evaluation in real-application in the American and Feather River basins; and c) peer-reviewed articles and conference presentations, reporting the work and findings in the project.

Evaluation Criterion D — Dissemination of Results

D1. Describe how the tools, frameworks, or analyses being developed will be disseminated, communicated, or made available to water resources managers who may be interested in the results.

All data in the project will be stored and shared in a data management system. The data in the data-management system will be conveniently and in a user-friendly way shared with collaborators, stakeholders, and interested users through the web service. More informatively, the important hydrologic information will be visualized through an online dashboard, which is publicly accessible for use by all water resources managers at local, regional, state, and federal agencies, and other interested users. The prototype system, data, tools, and analyses in the project will be also transferred to and disseminated in journal articles and conference presentations.

Evaluation Criterion E — Department of the Interior Priorities

E1. Explain how your project supports Department of the Interior Priorities (or at least one priority).

The proposed project supports the Department of the Interior priorities of *1 creating a conservation stewardship legacy second only to Teddy Roosevelt*, *3 restoring trust with local communities, and 4 striking a regulatory balance*.

Priority 1a. Utilize science to identify best practices to manage land and water resources and adapt to changes in the environment: The advanced knowledge and real-time data of rain-snow transition zone help to more efficient and reliable management of water resources in American and Feather River basins. The data and online dashboard provided by the project will also help identify the best practices in integrated management to cope with future heavy precipitation events. The system can be scaled across the Sierra Nevada and broader western United States.

Priority 1d. Review DOI water storage, transportation, and distribution systems to identify opportunities to resolve conflicts and expand capacity: The project supports the integrated management of water resources, which benefits the interconnected water storage and distribution systems in the SWP and CVP, and helps resolve the conflicts between various water users and agencies. The water supply capacity could be potentially expanded by informed operations in the multipurpose reservoirs with more accurate forecasting data, e.g. the data provided by this project.

Priority 3a. Be a better neighbor with those closest to our resources by improving dialogue and relationships with persons and entities bordering our lands: The project will help improve the reservoir operation to maintain safe water levels and secure water supply. This would help avoid flooding emergencies, making a better neighbor to water users and surrounding communities.

Priority 4a. Reduce the administrative and regulatory burden imposed on U.S. industry and the public: The online dashboard from the project will provide important hydrologic data to support the decision making, inform the reservoir operation, and improve flood modeling. The more accurate hydrologic information would reduce the uncertainty of flood forecasts, and can potentially reduce the needs of field monitoring during flood seasons, the chance of issuing a flood mobilization, and the emergency costs during a flood event.

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2. PROJECT BUDGET

2.1. Funding plan and letters of funding commitment

The California Department of Water Resources (DWR) has committed the non-federal share of project costs. Please see the attached letter in Appendix A.

2.2. Budget proposal

The detailed budget proposal is shown in Table 2 and total project cost is shown in Table 3.

Table 2. Budget proposal for project.

BUDGET ITEM DESCRIPTION	COMPUTATION		RECIPIENT FUNDING	OTHER FUNDING	RECLAMATION FUNDING	TOTAL COST
	$/Unit and Unit	Quantity				
1. SALARIES AND WAGES --Position title x hourly wage/salary x est. hours for assisted activity. Describe this information for each position.						
Roger Bales	$158.57/hr.	391.5		$31,041	$31,040	$62,081
Postdoc level 5	$30.25	6264		$94,749	$94,748	$189,497
Programmer	$35.33	1914		$33,813	$33,813	$67,626
Undergraduate assistant	$15.40	1174		$18,082	$18,082	$36,164
2. FRINGE BENEFITS – Explain the type of fringe benefits and how are they applied to various categories of personnel.						
Roger Bales	4.9%			$1,532	$1,531	$3,063
Postdoc level 5	42%			$40,181	$40,181	$80,362
Programmer	60%			$20,613	$20,612	$41,225
Undergraduate assistant	4.9%			$892	$892	$1,784
3. TRAVEL—dates; location of travel; method of travel x estimated cost; who will travel						
Mileage	.58/mile	1,897 mi/yr		$1,650	$1,650	$3,300
Hotel & meals	$200/day	8/yr		$2,400	$2,400	$4,800
Meeting registration	$400/meeting	2/yr		$1,200	$1,200	$2,400
4. EQUIPMENT—Leased Equipment use rate + hourly wage/salary x est. hours for assisted activity—Describe equipment to be purchased, unit price, # of units for all equipment to be purchased or leased for assisted activity: Do not list contractor supplied equipment here.						
5. SUPPLIES/MATERIALS--Describe all major types of supplies/materials, unit price, # of units, etc., to be used on this assisted activity.						
Computer equipment	4 total			$4,200	$4,200	$8,400
Accessories, supplies, phone				$4,050	$4,050	$8,100
Publication fees				$900	$900	$1,800
6. CONTRACTUAL/ CONSTRUCTION—Explain any contracts or sub-Agreements that will be awarded, why needed. Explain contractor qualifications and how the contractor will be selected.						
7. ENVIRONMENTAL and REGULATORY COMPLIANCE COSTS – Reference cost incurred by Reclamation or the applicant in complying with environmental regulations applicable to this Program, which include NEPA, ESA, NHPA etc.						
8. OTHER –List any other cost elements necessary for your project; such as extra reporting, or contingencies in a construction contract.						
TOTAL DIRECT COSTS--				$255,302	$255,299	$510,061
9. INDIRECT COSTS - What is the percentage rate**%.** If you do not have a Federally-approved Indirect Cost Rate Agreement or if unapproved rates are used - Explain Why.						
Rate of 17.5%				$44,678	$44.677	$89,355
TOTAL PROJECT/ACTIVITY				$299,981	$299,976	$599.957

Table 3. Total project costs.

SOURCE	AMOUNT
Costs to be reimbursed with the requested Federal funding	$299,976
Costs to be paid by the agency partner (DWR)	$299.981
Value of third-party contributions	$0
TOTAL PROJECT COST	**$599,957**

2.3. Budget narrative

Salaries and Wages

The PI (Bales will supervise the postdoc, interface with agency partners, and be responsible for overall project success (summer salary equivalent to 75% of one month each year). A 100% postdoc (Guotao Cui), who will carry out the project and work closely with DWR and other agencies is budgeted at 100% for 3 years. The programmer (Xiande Meng) will develop the data management system and dashboard components, including data processing (budgeted at 25% in year 1 and 33.3% in years 2-3). An undergraduate student will work with the postdoc and programmer (25% academic year and 75% summer).

Fringe Benefits
Standard university rates are used: 4.9% for the PI summer salary, 42% for the postdoc, 60% for the programmer, and 4.9% for the undergraduate.

Travel
The budget for travel includes $1,200 each for the PI and postdoc to attend scientific meetings each year, plus $1,100 each year for project meetings. Scientific meetings are budgeted for the American Geophysical Union, in December of each year in San Francisco, at $400 for meeting registration, and $600 for 4 nights hotel, plus $200 for 4 days meals, for a total of $1,200 each for the PI and postdoc each year. Mileage (1,897 mi per year) is for traveling from Merced for 4 meetings per year in Sacramento (240 miles each, 960 miles total), plus one trip per year to visit field sites in the Feather and American River basins (340 miles each, 680 miles total), plus one trip to San Francisco for the scientific meeting (257 miles). We use the university mileage rate of $0.58 per mile.

Equipment
None

Materials and Supplies
The budget includes 2 notebook computers in year 1, and one each in years 2-3, at $2,100 each. Additional computer accessories, office supplies and phone for the postdoc are also included ($2,000 in year 1, $3,200 in year 2, and $2,900 in year 3).

Contractual
None

Third-Party In-Kind Contributions
None

Other Expenses
None

Total Direct Costs
Total Direct costs is $510,601.00

Indirect Costs

Calculated at 17.5% MTDC $510,601 to give us $89,355.00

Total Project costs is $599,957.00 ($510,601 + $89,355)

3. ENVIRONMENTAL AND CULTURAL RESOURCES COMPLIANCE

The proposed planning project does not require compliance review.

4. REQUIRED PERMITS OR APPROVALS

No permits or approvals are required for the proposed project.

5. LETTER OF SUPPORT

The letter from the DWR for participating and supporting this proposed project application is attached in Appendix A.

6. OFFICIAL RESOLUTIONS

Not applicable.

7. UNIQUE ENTITY IDENTIFIER AND SYSTEM FOR AWARD MANAGEMENT

The applicant SNRI of University of California, Merced is currently registered in the System for Award Management (SAM). The DUNS number for the applicant is 113645084. The SAM registration will be maintained throughout the grant period.