Improving seasonal streamflow forecasts for irrigation districts by incorporating soil moisture information derived from remote sensing

Submitted to: Department of the Interior Bureau of Reclamation WaterSMART Applied Sciences program

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1. Executive Summary October 28, 2019

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Project Summary: Surface water managers in the Great Plains face major challenges due to the region's drought-prone climate and large inter-annual variability in rainfall and streamflow, and they do not have access to seasonal streamflow forecasts like those widely-used in the snow-dominated watersheds of the western US. Recently completed work by the PIs shows that in-situ soil moisture measurements can be used to produce accurate streamflow forecasts in rainfall-dominated regions like the Great Plains and are able to ***provide >50% improvement*** over streamflow forecasts based on antecedent precipitation alone. However, the use of this method is currently restricted to watersheds where data from in-situ soil moisture monitoring stations are readily available. We hypothesize that utilizing remotely-sensed soil moisture data will allow the creation of similarly effective seasonal streamflow forecasts for improved water management in areas lacking in-situ soil moisture monitoring networks. We propose to broaden the applicability of our statistical streamflow forecasting approach by incorporating a relatively new retrospective soil moisture product called Soil MERGE (SMERGE). SMERGE is a daily root zone (0-40 cm) soil moisture product derived from a combination of remotely-sensed soil moisture data and the North American Land Data Assimilation System (NLDAS-2) model. This product is available across the contiguous U.S. from 1979-2016 and will be used to train statistical models that produce seasonal streamflow forecasts for partnering surface water irrigation districts associated with Bureau of Reclamation projects in the central U.S. These models will be tested and applied operationally using soil moisture from NASA's Soil Moisture Active-Passive (SMAP) satellite, which are available globally every day after March 30, 2015. The approaches developed will be suitable for subsequent expansion to any rainfall-dominated watershed in the U.S. This research relates directly to the goals of the current FOA in that the successful completion of the project will improve the accuracy and adoption of streamflow forecasts, which are useful for reservoir management in rainfall-dominated watersheds. The project will provide new tools for surface water managers, support improved irrigation water supply management, and enhance the ability of reservoir operators to anticipate and respond to extreme events such as droughts and floods.

Funds received would be used to support a postdoctoral research associate. If selected, the project would begin when funds are distributed and conclude after one year's time. The proposed project is not located on a Federal facility.

2. Technical Project Description and Milestones

2.1 Overview and Objectives

Surface water irrigation districts in the Great Plains are subject to frequent droughts that reduce water availability, potentially leading to crop failures, economic loss, and serious conflicts among water users. The primary operational forecasting method currently in use in the region, developed by the National Weather Service (NWS) River Forecasting Centers (RFCs), was intended to predict flash flooding rather than to inform surface water management decisions and does not incorporate soil moisture information, which has been proven by the project team and others to increase streamflow forecast accuracy. The few streamflow forecasting methods which have been developed for surface water management purposes in rainfall-dominated regions east of the Rocky Mountains are limited in geographic extent, remain largely non-operational, and are generally less skillful than those used in the snow-dominated West. This combination of inadequate forecast availability and low forecast accuracy reduces the effectiveness of these methods, leaving surface water resources and the irrigation districts which rely upon them vulnerable. There is a clear need for improved streamflow forecasting methods to better inform surface water management decisions in the Great Plains.

The long-term goal of our work is to develop applications of soil moisture data which increase our ability to sustainably manage water resources. ***The overall objective of this proposal is to create seasonal streamflow forecasts utilizing remotely-sensed soil moisture data for improved water management in rainfall-dominated watersheds***. Results of a recently completed study by the PIs show that principal components analysis and regression (PCR) forecasting models which incorporate in-situ soil moisture measurements are capable of producing accurate streamflow forecasts in rainfall-dominated areas and that soil moisture data are able to provide >50% improvement in accuracy over precipitation-based forecasts. However, the use of this method is currently restricted to areas where data from in-situ soil moisture monitoring stations are readily available. We hypothesize that the use of a remotely-sensed soil moisture data product will allow the forecasting method to be applied in areas lacking in-situ soil moisture monitoring networks while preserving the effectiveness of the method.

The proposed work will build upon previous work by the PIs and is the next logical step in our efforts to support the development of useful streamflow forecasting methods to inform surface water management throughout the Great Plains. This team is uniquely qualified with expertise in large-scale soil moisture monitoring, hydrological modeling and model development, and knowledge of the challenges faced by water resource managers in the region. To accomplish our overall objective, we propose the following specific aims:

Aim 1. Create and evaluate seasonal streamflow forecasts by assimilating remotely-sensed soil moisture data into a modified PCR forecasting approach. Focusing on key watersheds that support Bureau of Reclamation projects in the Great Plains, we will develop and evaluate a seasonal streamflow forecasting approach which is trained using a long-term retrospective soil moisture product called Soil MERGE (SMERGE) and can be implemented operationally using NASA's newest soil moisture satellite, Soil Moisture Active-Passive (SMAP). Streamflow forecasts will be developed with lead times of up to three months, will target the four months of greatest observed historical streamflow, and will be evaluated using streamflow measurements from USGS stream gauges.

Aim 2. Engage irrigation district partners and other end users to increase utilization of the resulting seasonal streamflow forecasts. As Category B applicants, we will rely on our project partners from the Lugert-Altus Irrigation District in southwest Oklahoma, the Kansas Bostwick Irrigation District, and the Frenchman-Cambridge Irrigation District in Nebraska to provide input and feedback throughout the project regarding the optimization and use of the seasonal streamflow forecasts.

The proposed work will directly address the goal of the current FOA to "improve use of forecasts to inform surface water availability and the use of technology to increase water reliability" by leveraging recently-developed forecasting methods and data sources to provide timely, accurate predictions of future surface water availability. Additionally, the project aims are well-aligned with the overall objective of the Bureau's WaterSMART Applied Sciences program to "develop hydrologic information and water management tools and improve modeling and forecasting capabilities." When the project is completed, we expect to be able provide: 1) evaluations of the suitability of remote sensing soil moisture products for use in streamflow forecast development, 2) a modified streamflow forecasting approach trained using historical SMERGE soil moisture data, and 3) accurate operational streamflow forecasts which incorporate near real-time SMAP soil moisture data and can be used to improve decision making by surface water managers. The successful completion of the project will yield the first widely-applicable seasonal streamflow forecasts for improved water management in rainfall-dominated watersheds. These forecasts have the potential to improve surface water management and sustainability throughout large portions of the US.

2.2 Significance

Disastrous flooding throughout the Great Plains in the spring of 2019 highlighted the need for improved streamflow prediction methods to enhance surface water management and decision making. In Oklahoma, this flooding caused widespread evacuations as the Arkansas River rose to near-record levels following emergency releases from the Keystone Dam (Figure 1). This extreme flooding followed similar large-scale floods in Iowa, Nebraska, and Kansas and continued downstream

Figure 1. Homes in northeastern Oklahoma underwater due to record flooding.

into Arkansas and Louisiana. NOAA's National Centers for Environmental Information stated of the Arkansas River flood: "*Historic flooding impacts the Arkansas River Basin with damage to homes, agriculture, roads, bridges and levees focused across eastern Oklahoma and western Arkansas. Thousands of homes, cars and businesses were flooded due a combination of high rivers, levee failure, and persistently heavy rainfall from May 20 through mid-July*." Five lives were lost due this flooding event alone, and the total estimated economic costs of the flood have yet to be quantified.

Figure 2. Dead fish and a bare lakebed show the severity of the drought at Lugert-Altus Lake, OK.

Likewise, the ecological and economic losses suffered due to record low surface water levels during recent severe droughts throughout the Great Plains region further demonstrate that there is a need for improved streamflow prediction methods. The extreme drought throughout Oklahoma, Kansas, and Nebraska which began in 2010 and persisted in the region until 2015 had devastating impacts on agricultural water supplies. At Lake Altus-Lugert in southwestern Oklahoma, water levels dropped to record lows with lake capacity <10%, which resulted in a massive fish kill and halted irrigation releases from the lake for four consecutive years (Figure 2). This resulted in 40,000 acres of cropland to go unirrigated during those years, leading *crop indemnity payments in the district in excess of $223 million* to be made. Further north, this drought led to increased conflict between Kansas and Nebraska over irrigation water use from the Republican River.

Irrigated agriculture is the largest water user in the Great Plains, and a majority of the irrigation water withdrawals come from the High Plains, or Ogallala, aquifer. However, the Great Plains also encompasses more than one hundred surface water irrigation districts and similar water developments associated with Army Corps of Engineers reservoirs and/or Bureau of Reclamation infrastructure for water storage and delivery. These districts account for a substantial portion of agricultural water use in the region, and the sustainability of that use is threatened by frequent, multi-year droughts (Basara et al., 2013). Prior work in drought-prone regions has proven that seasonal streamflow forecasts can benefit irrigators by allowing them to make more informed risk-based management decisions (Chiew et al., 2003) and that the economic and knowledge benefits due to seasonal forecasts are greatest during drought and in areas with lower surface water volumes (Mushtaq et al., 2012; Mauer and Letternmaier, 2004).

Throughout most of the Great Plains, the primary operational streamflow forecasts are produced by the NWS-RFCs. These forecasts are produced using the Sacramento Soil Moisture Accounting (SAC) model, which produces probabilistic predictions of streamflow with up to a 90-day lead time. Unfortunately, this method performs poorly during the summer months in the Great Plains, which are often the months of greatest streamflow (Hashino et al., 2007). In general, operational forecasting systems for seasonal water supply in the Great Plains are less skillful than the forecast systems available in the western U.S. (Hashino et al., 2007; Pagano et al., 2004). This can be partly attributed to the fact that the Great Plains, unlike the western U.S., does not rely primarily on snowmelt runoff. As one Great Plains water manager noted, "*…forecast[s] targeting seasonal periods are unreliable in our geographical area…It is very difficult to provide water supply estimates to irrigators…*" (Raff et al., 2013). One reason for this lack of reliability is that current forecasting systems do not incorporate soil moisture observations, even though their potential to improve seasonal streamflow forecasts has been known since the 1930s (Rosenberg et al., 2013) Recently, however, work by the PIs has shown that accurate streamflow forecasts during the four months of greatest flow may be made by incorporating in-situ soil moisture information in a PCR forecasting model (see preliminary data). Additionally, several recent studies show that remotely-sensed soil moisture data can improve model streamflow estimates (Akbar et al., 2019; Koster et al., 2018).

The proposed work is significant because its successful completion will result in novel and useful streamflow forecasts which can be utilized by our irrigation district partners in Oklahoma, Kansas, and Nebraska, as well as by other districts, to improve the management and sustainability of the region's surface water irrigation resources. The forecasts developed here, with lead times up to 3 months, can be used by water managers to decrease releases when future streamflows are forecast to be low or to release water when forecast streamflow levels are high. The partnerships and end-user engagement that will result from this work will empower surface water managers in the Great Plains to make improved management decisions in the face of frequent droughts and an increasingly variable climate. These forecasts will assist irrigators and irrigation districts in making a wide array of management decisions such as water allocations, crop type and variety, and level of investment in crop inputs and insurance. Reliable water supply forecasts for surface water irrigation districts are expected to result in significant economic benefit to the irrigators themselves and to rural communities where irrigation drives employment and economic activity. Moreover, the broader impacts of the proposed project will extend well beyond agriculture to include potential improvements in reservoir management, hydropower generation, and environmental flows.

2.3 Project Locations

The proposed work will focus on key watersheds which supply water to reservoirs managed by our irrigation district partners in Oklahoma, Kansas, and Nebraska (Figures 3 and 4). These districts are responsible for supplying irrigation water to over 178,000 acres of farmland and play a critical role in distributing and managing surface water in the region, but each has faced difficulties in the recent past. The Lugert-Altus district in southwestern Oklahoma suffered ecologically and economically from the previously mentioned severe drought, which was shown to have been exacerbated by upstream water use (Krueger et al., 2017). The Bostwick irrigation district in north-central Kansas was awarded $2.5 million by the U.S. Supreme Court in 2015 as reparation for decreased irrigation water levels from the Republican River caused by increased upstream groundwater pumping in Nebraska.

Similarly, litigation regarding the use of water from the Frenchman-Cambridge Irrigation District in southern Nebraska was begun in 2013 by irrigators whose water supply from the Republican River was decreased by the state of Nebraska in order to maintain compliance with their Republican River Compact with the state of Kansas. Each of these irrigation districts and their watersheds are subject to frequent drought, often resulting in local and inter-state conflicts. It is evident that there is a need for improved streamflow forecasting methods to increase the districts' ability to manage available water resources, to prepare for future shortages, and to reduce water-related conflict in the region.

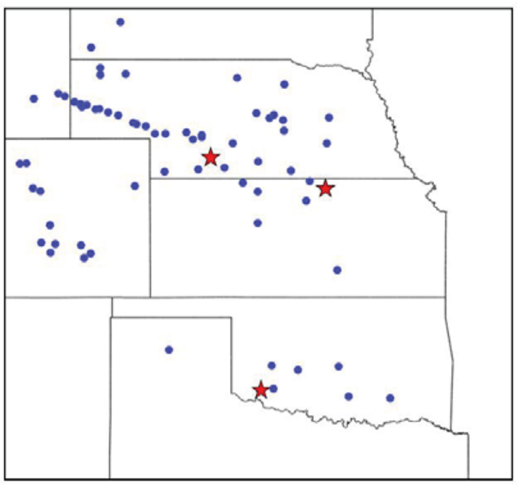

Figure 3. Locations of surface water irrigations districts, reclamation districts, and water delivery companies in OK, KS, and NE (blue dots). Stars mark the Lugert-Altus district in OK, the Bostwick district in KS, and the Frenchman-Cambridge district in NE.

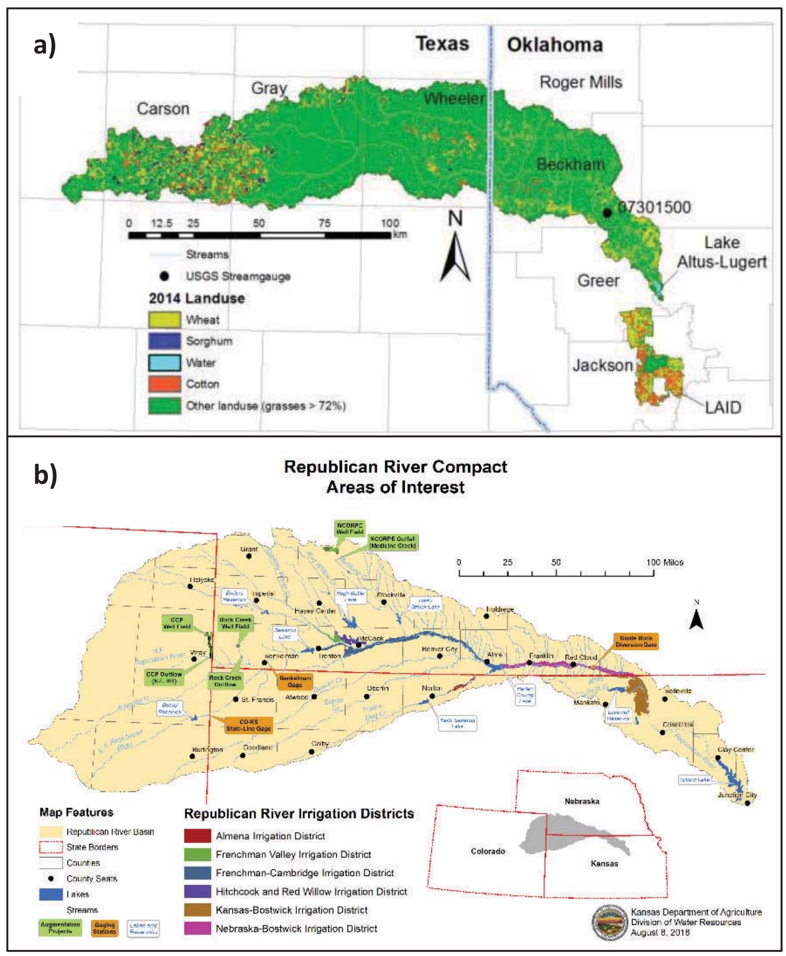

Figure 4. Top panel: The North Fork of the Red River watershed upstream from Lake Altus-Lugert. The Lugert-Altus Irrigation District (LAID) is south of Lake Altus-Lugert. Bottom panel: Republican River Irrigation Districts. The Frenchman-Cambridge Irrigation District (NE) is shown in blue and the Bostwick Irrigation District (KS) is shown in brown.

2.4 Preliminary data

Recently completed work by the PIs integrated antecedent precipitation and in-situ soil moisture data into a PCR model in order to produce seasonal streamflow forecasts in rainfall-dominated watersheds in Arizona, Oklahoma, and Georgia. These watersheds span a wide range of climatic conditions, with mean annual rainfall during the study period ranging from 307 mm yr^{-1} to 1131 mm yr^{-1}. Our results showed that forecasts derived from antecedent precipitation alone were often statistically insignificant, explaining at best 27% of the variability in seasonal streamflow. Forecast models which included soil moisture information, on the other hand, were found to be statistically significant in all watersheds and explained 67% to 87% of seasonal streamflow variability at the 0-month lead time (Figure 5).

In addition to improvements at the 0-month lead time, our results showed that forecasts which incorporated soil moisture were able to provide seasonal streamflow forecasts at lead

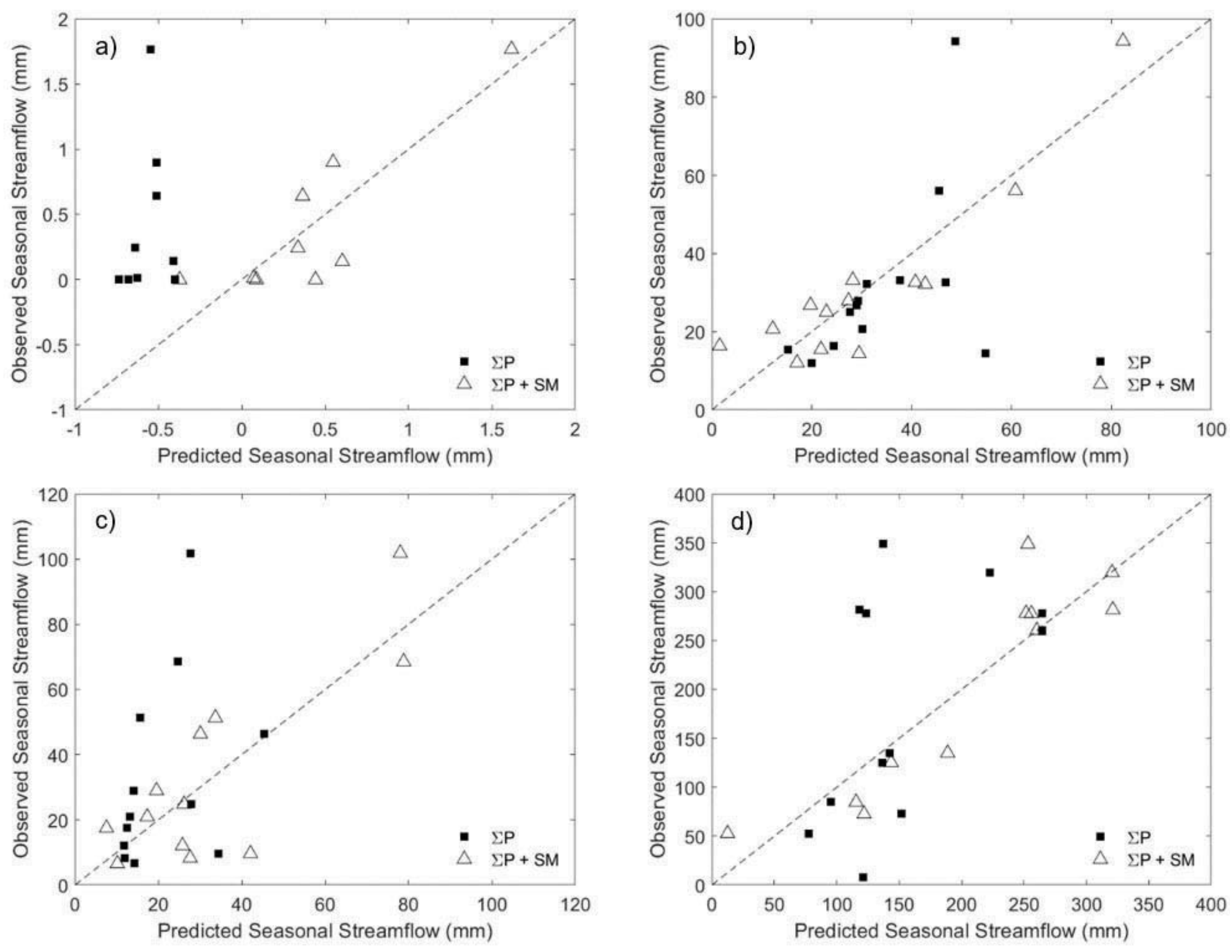

Figure 5. Yearly observed and predicted seasonal streamflow volumes for precipitation based (black squares) and precipitation + soil moisture based (triangles) forecasts in the Walnut Gulch, AZ (a), Fort Cobb, OK (b), Little Washita, OK (c), and Little River, GA (d) watersheds at the 0-month lead time. Improvements in forecast accuracy due to the inclusion of soil moisture data are evident in all watersheds.

times up to three months and, compared with forecasts including only precipitation data, improved model R^2 values by 0.66, 0.62, 0.56, and 0.50 at the 0-, 1-, 2-, and 3-month lead times, respectively. The incorporation of measured soil moisture data in the PCR method used for this work produced seasonal streamflow forecasts for rainfall-dominated watersheds with accuracies comparable to those previously reported in snow-dominated watersheds (Harpold et al., 2017). To our knowledge, this study provided the first evidence of the usefulness of the PCR streamflow forecasting method in rainfall-dominated regions, as well as the first proof of seasonal streamflow forecast accuracy improvement in these regions due to the incorporation of measured soil moisture data.

2.5 Methods

Aim 1. Create and evaluate seasonal streamflow forecasts by assimilating remotely-sensed soil moisture data into a modified PCR forecasting approach. Focusing on key watersheds that support Bureau of Reclamation projects in the Great Plains, we will develop and evaluate a seasonal streamflow forecasting approach which is trained using a long-term retrospective soil moisture product called Soil MERGE (SMERGE) and can be implemented operationally using NASA's newest soil moisture satellite, Soil Moisture Active-Passive (SMAP). Streamflow forecasts will be developed at up to a three-month lead time, will target the four months of greatest observed historical streamflow, and will be evaluated using streamflow measurements from USGS stream gauges.

To meet this aim, we will modify a well-established method of streamflow forecasting called principal components analysis and regression. Principal components analysis and regression has been used operationally for decades by the Natural Resources Conservation Service (NRCS) in the snow-dominated mountain West, where snowmelt is the primary source of surface water runoff (Garen, 1992). This method is a well-known multivariate technique for incorporating data from multiple monitoring sites into a statistical model while minimizing the effects of intercorrelation between measured variables (Shlens, 2014). In the West, snow water equivalent data are traditionally used as the primary model input. However, the PIs recently demonstrated that the method may be adapted for use in rainfall-dominated regions by incorporating antecedent precipitation and soil moisture information as inputs.

Under Aim 1, we propose to modify and broaden the applicability of our PCR approach by incorporating a new soil moisture product called Soil MERGE (SMERGE). SMERGE is a daily root zone (0-40 cm) soil moisture product derived from a combination of remotely-sensed soil moisture data and the North American Land Data Assimilation System (NLDAS-2) model (Figure 6) (Tobin et al., 2017). This product is available at 0.125° or ~14 km spatial resolution across the contiguous U.S. for the years 1979-2016. SMERGE data will be normalized using *z*-scores, a common statistical technique, and used to develop a modified PCR model that will allow for seasonal streamflow forecasts to be made at lead times up to 3 months in rainfall-dominated watersheds lacking in-situ soil moisture sensors.

In addition to SMERGE data, daily precipitation data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group will be incorporated into the modified PCR model that will be applied in each study watershed. Daily PRISM precipitation data are available from 1981 to the present at an ~800 km resolution, with historical observations available prior to 1981. PRISM antecedent precipitation data and normalized SMERGE soil moisture data will be utilized as inputs for principal components analysis for each watershed. This will result in the creation of a number of principal components, or non-correlated linear combinations of the input variables, for each watershed. We will use a *t*-test ($p < 0.10$) to identify the statistically significant principal components, which we will use to develop a principal components regression equation for each watershed. These regressions will then be used to forecast streamflow for the 4-month "season" of the year which has historically had the greatest average streamflow total.

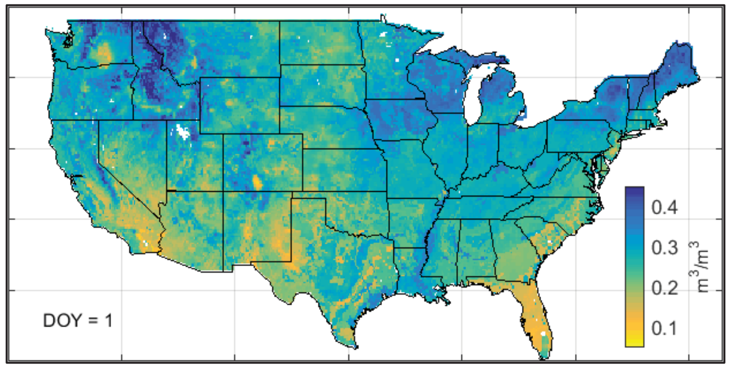

Figure 6. Snapshot of SMERGE data product on January 1, 2015. Follow image link to see a 365-day illustration of soil moisture dynamics.

By targeting the four months of greatest streamflow in each watershed, we will provide critical information for water managers regarding flows during the most important months of the year. Confidence intervals of forecast seasonal streamflow totals will be provided for each year, and estimated seasonal streamflow volumes will be compared to measured streamflow at USGS stream gauges for each year. Following Harpold et al. (2017) and recent work by the PIs, the accuracy of the forecasts will be evaluated using typical statistical measures: the coefficient of determination (R^2), the root mean squared error (RMSE), the ratio of the RMSE to the standard deviation of observed streamflow (RSR), and the percent difference between forecast and observed streamflow at USGS stream gauges.

In order to predict seasonal streamflow for years after 2016, we will use normalized root zone soil moisture data (L4 product) from NASA's Soil Moisture Active-Passive (SMAP) satellite (Figure 7) in the regression equations developed previously using SMERGE. This approach is necessary because the SMERGE product is not available after 2016 and is therefore not able to be used operationally, and because the best way to validate the ability of a forecasting method is to test it using an

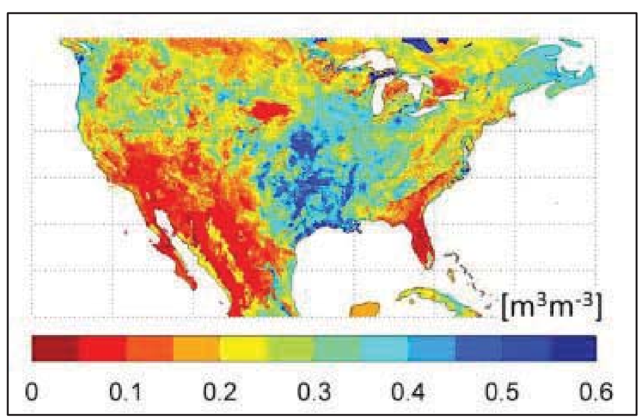

Figure 7. Map of SMAP Level 4 root zone soil moisture over the contiguous U.S. on May 29, 2015. Source: Reichle et al. (2016).

independent data set (Kerk, 2012). SMAP L4 data are available globally every 3 hours at a 9 km resolution from March 31, 2015 until the present with only a 7-day latency. The normalization of PCR input data is common (Haan, 1977) and will allow SMERGE and SMAP data to be used interchangeably within the PCR model (Figure 8). This approach will allow us to develop the necessary regression equations using the long-term SMERGE soil moisture dataset and will allow us to test the performance of the resulting forecasts using inputs from an independent dataset (SMAP). Additionally, the use of SMAP data will allow the method to be used operationally now and throughout the life of the SMAP mission.

In order to operationalize the forecasts, computer codes will be developed which automatically download the necessary data and incorporate those data into the PCR model. SMERGE data will be used only for training the PCR model and are not needed for the operational use of the method. PRISM precipitation data and SMAP soil moisture data will be downloaded automatically using an anonymous File Transfer Protocol (FTP) server and a Hypertext Transfer Protocol Secure (HTTPS) protocol, respectively. This automation will allow forecasts to be shared and used easily in the future, both by our research team and by our project partners, and will produce the necessary forecasts with little effort required on the part of the user.

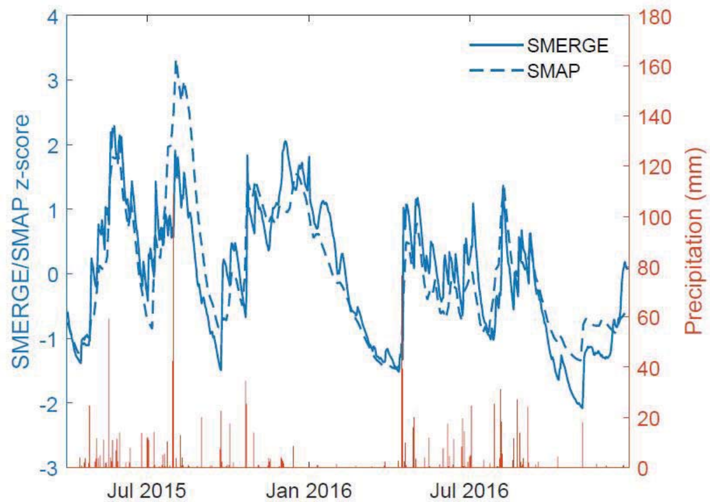

Figure 8. Z-scores of mean daily SMERGE and SMAP L3 soil moisture data for Cimarron County, OK during the period when the datasets overlap (Apr 2015-Dec 2016).

Aim 2. Engage irrigation district partners and other end users to increase utilization of the resulting seasonal streamflow forecasts. As Category B applicants, we will rely on our project partners from the Lugert-Altus Irrigation District in southwest Oklahoma, the Kansas Bostwick Irrigation District, and the Frenchman-Cambridge Irrigation District in Nebraska to provide input and feedback throughout the project regarding the optimization and use of the seasonal streamflow forecasts.

To ensure that this project results in sustained improvements in forecast availability and agricultural water supply management, we are committed to maintaining regular communication with our irrigation district partners. We have identified representative surface water irrigation districts in which to focus our end-user engagement, one each in Oklahoma, Kansas, and Nebraska. These are the Lugert-Altus Irrigation District in southwest Oklahoma, the Kansas Bostwick Irrigation District, and the Frenchman-Cambridge Irrigation District in Nebraska. We will engage these partners at least quarterly through phone conversations and teleconferences to learn how to improve the delivery format of seasonal streamflow forecasts and to lower barriers that may prevent the use of these forecasts in agricultural water management. Additionally, we will provide these end-users with training in how to utilize the seasonal streamflow forecasts produced by this project and how to use that information to make management decisions. Such training was identified as a key need by Raff et al. (2013), who stated "*Training is identified as needed for nontechnical stakeholders who are not fully informed about water management missions and the policies that govern how information is utilized. Additionally, training is needed to better inform water managers of the principles associated with applying probabilistic forecast information to support risk-based decision making.*"

2.6 Project Milestones

The development of the proposed streamflow forecasts will build upon recent work by the PIs, which will facilitate the completion of the project in one year. Due to this prior work, only minor changes will need to be made to computer programs in order to incorporate SMERGE data and develop a new forecasting model and to validate the model using independent SMAP data. In the first quarter, we expect to collect the necessary SMERGE and PRISM data, perform quality control on the data, and prepare the data for use in the PCR model. During the second quarter, we will modify existing computer programs, integrate the new data sources into the PCR model framework, and develop streamflow forecasting models for the target watersheds. In the third quarter, we will test the validity of the developed PCR model using independent SMAP soil moisture data. Finally, we will publish our results and share our findings at professional meetings. The computer codes needed to generate the forecasts operationally will be provided to project partners and made publicly available through an accepted online repository such as GitHub. We expect to have seasonal forecasts readily available to our project partners at the completion of the project, with potential to expand the method to other watersheds in the future.

	Year 1			
	Quarter 1	**Quarter 2**	**Quarter 3**	**Quarter 4**
Aim 1	Collect necessary SMERGE and PRISM data	Modify existing code to develop new PCR streamflow forecasting model	Test PCR model using independent SMAP data	Publish results and deliver computer codes for forecasting system
Aim 2	Contact project partners regarding needs and desired outputs	Share project progress and get feedback from partners	Implement changes suggested by partners	Share results with project partners and train partners on how to use forecasts

3. Data Management Practices

Data used in this project will include SMERGE and SMAP soil moisture data, PRISM precipitation data, and observed streamflow data collected by the USGS. These data will be stored as .csv or similar text file formats and kept in a Dropbox folder shared by the PIs. The source and collection date(s) of all data will be recorded in a separate document, as will metadata files describing the data and how they are being used. All data used, if not open source and available to the public, will be released along with any peer-reviewed publications that result from the study.

4. Evaluation Criteria

4.1 Evaluation Criterion A — Benefits to Water Supply Reliability

1. Describe the *water management issue(s)* that your project will address. For example, will your project address water supply shortfalls or uncertainties, the need to meet competing demands for water, complications arising from drought, conflicts over water, or other water management issues? Describe the severity of the water management issues to be addressed through your project.

Response: The proposed streamflow forecasting approach will increase water supply reliability by reducing uncertainties about surface water availability and irrigation water supplies for the coming season. The forecasts will facilitate water management decisions that better meet competing demands between upstream and downstream users, mitigate water shortages arising from drought, and reduce water-related conflicts. Each of these issues frequently occur in the watersheds and irrigation districts on which this project is focused. Additionally, the limited availability of streamflow forecasts in the Great Plains and the increasingly variable weather patterns in the region further increase the vulnerability of surface water resources and those who rely upon them. This vulnerability is often exacerbated by drought, and disagreements among users regarding equitable water use are common in the region. These serious threats to surface water sustainability in the Great Plains will be addressed through the proposed research.

2. Explain *how* your project will address the water management issues identified in your response to the preceding bullet. In your response, please explain how your project will contribute to one or more of the following water management objectives and provide support for your response:

a. water supply reliability,
b. management of water deliveries,
c. water marketing activities,
d. drought management activities,
e. conjunctive use of ground and surface water,
f. water rights administration,
g. ability to meet endangered species requirements,
h. watershed health,
i. conservation and efficiency, or
j. other improvements to water supply reliability.

Response: Our project will contribute directly to the improvement of surface *water supply reliability* by increasing the accuracy of seasonal streamflow forecasts and by engaging irrigation district managers to utilize this new information in order to improve water management strategies. This will, in turn, allow for better, more informed *management of irrigation water deliveries* to producers and other users. This project will improve *drought management activities* by supporting the development of forecasts which will be able to provide information regarding future streamflows months in advance. Finally, in addition to benefits to agricultural water users, the proposed work will better inform the decisions of reservoir operators in delegating water to various *conservation strategies*, such as the maintenance of in-stream flows.

3. Describe *to what extent* your project will benefit one of the water management objectives listed in the preceding bullets. In other words, describe the significance or magnitude of the benefits of your project, either quantitatively or qualitatively, in meeting one or more of the listed objectives.

Response: Because there are currently no operational streamflow forecasts in the Great Plains, the proposed work has strong potential to greatly improve water supply reliability and management in the region. The successful completion of the project should lead not only to more information regarding future streamflows, but also to the active use of the forecasts themselves by our partners and other irrigation districts.

4. Explain how your project complements other similar applicable to the area where the project is located. Will your project complement or add value to other, similar efforts in the area, rather than duplicate or complicate those efforts? Applicant should make a reasonable effort to explore and briefly describe related ongoing projects.

Response: The proposed work is similar to a study previously funded by the WaterSMART program in Oklahoma which focused on quantifying risks to the Foss and Fort Cobb surface water reservoirs associated with drought. While the current project has implications for reservoir management during drought, our primary objective is to develop an accurate streamflow forecasting method and to increase the use of streamflow forecasts by water managers in order to improve the sustainability of surface water resources throughout the Great Plains. To our knowledge, the proposed project is the first in the region with the goal of developing operational streamflow forecasts that will be used directly by irrigation districts.

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

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

a. Explain who has expressed the need and describe how and where the need for the project was identified (even if the applicant is the primary beneficiary of the project). For example, was the need identified as part of a prior water resources planning effort, through the course of normal operations, or raised by stakeholders? Provide support for your response (e.g., identify the entities that have expressed a need or cite planning or other documents expressing a need for the project).

Response: The proposed work relates directly to multiple needs identified by Raff et al. (2013), a major study on end-user information needs for improved water management. That study, led by the US Army Corp of Engineers, the Bureau of Reclamation, and the National Oceanic and Atmospheric Administration, identified key needs such as "developing enhanced monitoring and forecast products," and "making…streamflow forecasts more skillful and reliable." The current work is the logical next step forward in a series of projects by the PIs which seek to meet these needs by improving seasonal streamflow forecasts, in order to increase the sustainability and improve the management of surface water reservoirs in the Great Plains. Our project partners– managers of irrigation districts in Oklahoma, Kansas, and Nebraska– have agreed that accurate streamflow forecasts are an important step forward in improving reservoir management that would aid in planning water deliveries.

b. Provide letters of support from any resource managers, stakeholders or partners that have stated that they will benefit from the project, or, for Category B applicants, letters of participation from partners who have committed to participate in the proposed project. Identify any contribution (e.g., cost share, staff time, or other resources) by partners other than the applicant to the non-Federal cost share requirement for the project.

Response: Letters of support from our project partners are included below. The primary contribution of these partners, according to Aim #2 above, will be to provide regular input and feedback to the PIs regarding the usefulness of the forecasts developed in order that the forecasts may be effective and used operationally by the partners.

Note: Category B applicants will be evaluated under this criterion based on the *extent* of demonstrated support for their project beyond meeting this minimum requirement (i.e., to what extent project partners are committed to participating in the project).

2. 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?

Response: Yes; the successful completion of the proposed project will result the development of streamflow forecasts that will be available for immediate use to our project partners and which may be developed for any additional rainfed watersheds in the region. Given the level of support for the project by our partners and our intentions to make the forecasts as user-friendly as possible, we believe that these forecasts are highly likely to be used to inform water management decisions in these watersheds.

a. How will the project results be used?

Response: The forecasts resulting from this project will be used by irrigation district managers to inform water release decisions, improve drought responses, and improve reservoir operations. For example, if predicted streamflow is low, water managers may decide to decrease releases, or if predicted streamflow volumes are high, managers may choose to release more water in preparation for high future streamflows. In southeast Australia, seasonal streamflow forecasts similar to those proposed here have been used to optimize water restriction rules in an urban area and to allow irrigators to make more informed risk-based management decisions in two irrigated systems (Chiew et al., 2003).

b. Will the results of your project inform water resource management actions and decisions immediately upon completion of the project, or will additional work be required?

Response: The successful completion of the proposed project will result the development of streamflow forecasts that will be available for immediate use to our project partners. Additional forecasts may be developed for any additional rainfed watersheds in the region in the future.

c. Will the results of your project be transferrable to other users and locations?

Response: Yes; the method used here to develop streamflow forecasts is widely applicable and may be developed for any additional rainfed watersheds in the region in the future.

d. If the applicant is not the primary beneficiary of the project (e.g., if the applicant is a university or research institute), describe how the project beneficiaries have been or will be involved in planning and implementing the project?

Response: Our project partners will be essential for the development of streamflow forecasts which will be useful to surface water managers in the region. We will rely upon feedback from these partners throughout the project regarding the usability of project deliverables. Input from our partners will be essential for developing a product that is easily understood, used, and operationalized by end users.

4.3 Evaluation Criterion C — Project Implementation

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

Response: Aim 1. Create and evaluate seasonal streamflow forecasts by assimilating remotely-sensed soil moisture data into a modified PCR forecasting approach. Focusing on the key watersheds mentioned above, we will develop and evaluate a seasonal streamflow forecasting approach which is trained using a long-term retrospective soil moisture product called Soil MERGE (SMERGE) and can be implemented operationally using NASA's newest soil moisture satellite, Soil Moisture Active-Passive (SMAP). These streamflow forecasts will be developed with lead times up to three months, will target the four months of greatest observed historical streamflow, and will be evaluated using streamflow measurements from USGS stream gauges.

Building on prior work by the PIs, we will modify a well-established PCR streamflow forecasting model to incorporated remotely-sensed soil moisture information. This will involve acquiring the necessary data, modifying portions of existing computer programs, developing the PCR model using SMERGE soil moisture data, and validating the model using the independent SMAP dataset. There is strong support for the success of this approach, as the PCR model has been used to predict seasonal streamflow for decades in the snow-dominated mountain West (Garen, 1992), has been show to produce more accurate results when considering soil moisture data (Harpold et al., 2017), and has recently been shown by the PIs to be capable of producing useful forecasts even in rainfall-dominated watersheds (manuscript under review, see preliminary data).

Aim 2. Engage irrigation district partners and other end users to increase utilization of the resulting seasonal streamflow forecasts. As Category B applicants, we will rely on our project partners from the Lugert-Altus Irrigation District in southwest Oklahoma, the Kansas Bostwick Irrigation District, and the Frenchman-Cambridge Irrigation District in Nebraska to provide input and feedback throughout the project regarding the optimization and use of the seasonal streamflow forecasts.

To ensure that this project results in sustained improvements in forecast availability and management of agricultural water supplies, we are committed to maintaining regular communication with our irrigation district partners. We will regularly engage these partners through phone conversations and teleconferences to learn how to improve the delivery format of seasonal streamflow forecasts and to lower barriers that may prevent the use of these forecasts in agricultural water management. Additionally, we will provide these end-users with training in how to utilize the seasonal streamflow forecasts produced by this project and how to use that information to make management decisions.

2. 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.

Response: The development of the proposed streamflow forecasts will build upon recent work by the PIs, which will facilitate the completion of the project in one year. Due to this prior work, only minor changes will need to be made to computer programs in order to incorporate SMERGE data and develop a new forecasting model and to validate the model using independent SMAP data. In the first quarter, we expect to collect the necessary SMERGE and PRISM data, perform quality control on the data, and prepare the data for use in the PCR model. During the second quarter, we will modify existing computer programs, integrate the new data sources into the PCR model framework, and develop streamflow forecasting models for the target watersheds. In the third quarter, we will test the validity of the developed PCR model using independent SMAP soil moisture data. Finally, we will publish our results and share our findings at professional meetings. We expect to have seasonal forecasts readily available to our project partners at the completion of the project, with potential to expand the method to other basins in the future.

	Year 1			
	Quarter 1	**Quarter 2**	**Quarter 3**	**Quarter 4**
Aim 1	Collect necessary SMERGE and PRISM data	Modify existing code to develop new PCR streamflow forecasting model	Test PCR model using independent SMAP data	Publish results and deliver computer codes for forecasting system
Aim 2	Contact project partners regarding needs and desired outputs	Share project progress and get feedback from partners	Implement changes suggested by partners	Share results with project partners and train partners on how to use forecasts

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

Response: SMERGE is a recently-developed database which contains daily soil moisture data (0-40 cm) at ~14 km resolution for the contiguous U.S. for the years 1979-2016. SMERGE data are derived from a combination of remotely-sensed soil moisture data and the North American Land Data Assimilation System (NLDAS-2) model and are readily available to the public online. Daily PRISM precipitation data are available online from 1981 to the present at an ~800 km resolution, with historical observations available prior to 1981. SMAP data are available globally every 3 hours at a 9 km resolution from March 31, 2015 until the present with a 7-day latency and are available online.

4. Identify staff with appropriate credentials and experience and describe their qualifications. Describe the process and criteria that will be used to select appropriate staff members for any positions that have not yet been filled. Describe any plans to request additional technical assistance from Reclamation or via a contract.

Response:

Tyson E. Ochsner, Ph.D.
Professor of Applied Soil Physics
Oklahoma State University
Department of Plant and Soil Sciences

Briana M. Wyatt
Doctoral Candidate
Oklahoma State University
Department of Plant and Soil Sciences

PI Ochsner has a strong record in agricultural water use research (Ochsner et al., 2010; Patrignani et al., 2012), delivering operational tools for hydrology and agricultural end-users (Patrignani and Ochsner, 2015), and first-hand knowledge of the challenges and constraints facing surface water irrigation districts and irrigators in the Great Plains.

PI Wyatt has expertise in hydrological modeling, developing PCR streamflow forecasts, and collecting and analyzing in-situ and remote sensing data from various sources. She has proven research success in using soil moisture information address water management challenges and has shown how such information can be used to estimate potential groundwater recharge (Wyatt et al., 2017).

a. Have the project team members accomplished projects similar in scope to the proposed project in the past either as a lead or team member?

Response: Yes; the PIs have recently successfully completed a similar project which incorporated in-situ soil moisture data into the PCR methodology in order to forecast streamflow in four watersheds in Arizona, Oklahoma, and Georgia (manuscript under review). Other previous work by PI Ochsner has focused on the causes of record low streamflows and water levels at Lake Altus-Lugert from 2010-2015, and determined that upstream water use was the primary driver (Kruger et al., 2017).

b. Is the project team capable of proceeding with tasks within the proposed project immediately upon entering into a financial assistance agreement? If not, please explain the reason for any anticipated delay.

Response: Yes; work on the project will begin immediately upon receiving funds.

5. Provide a summary description of the *products* that are anticipated to result from the project. These may include data, metadata, digital or electronic products, reports and publications.

Response: The primary products resulting from the proposed work will be in the form of operational streamflow forecasts that are made available to our project partners and which will be used to improve reservoir management and operations. Additionally, results from the project will be disseminated by presentations at professional meetings and by publication in peer-reviewed journals.

4.4 Evaluation Criterion D — Dissemination of Results

1. 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.

Response: Upon the completion of the project, products resulting from the proposed research will be shared with our project partners and these partners will be trained regarding how to utilize these forecasts in decision making. We will also publicize our results at local, state, and regional meetings, such as the annual Oklahoma Irrigation Conference, in order to increase awareness of forecast availability in the region. In so doing, we will aim to attract water managers from other irrigation districts that could benefit from the type of forecasts developed here.

a. If the applicant is the primary beneficiary of the project, explain how the project results will be communicated internally, and to interested stakeholders and interested water resources managers in the area, if appropriate.

Response: Not applicable

b. If the applicant is not the primary beneficiary of the project (e.g., universities or research institutes) describe how project results will be communicated to project partners and interested water resources managers in the area.

Response: Upon the completion of the project, results of the proposed research will be shared with our project partners and these partners will be trained regarding how to utilize the resulting streamflow forecasts in decision making. We will also publicize our results at local, state, and regional meetings in order to increase awareness of forecast availability in the region. In so doing, we will aim to attract water managers from other irrigation districts that could benefit from the type of forecasts developed here.

c. Explain why the chosen approach is the most effective way to disseminate the information to end users in a usable manner.

Response: Dissemination of project results at meetings allows for face-to-face interactions with water managers. The relationships built at such meetings are crucial to the adoption of research results by end users.

4.5 Evaluation Criterion E — Department of the Interior Priorities

1. *Creating a conservation stewardship legacy second only to Teddy Roosevelt*
a. utilize science to identify best practices to manage land and water resources and adapt to changes in the environment;
b. examine land use planning processes and land use designations that govern public use and access;
c. revise and streamline the environmental and regulatory review process while maintaining environmental standards;
d. review DOI water storage, transportation, and distribution systems to identify opportunities to resolve conflicts and expand capacity;
e. foster relationships with conservation organizations advocating for balanced stewardship and use of public lands;
f. identify and implement initiatives to expand access to DOI lands for hunting and fishing;
g. shift the balance towards providing greater public access to public lands over restrictions to access.

Response: The proposed work will serve to improve current best management practices for reservoir operations, and will allow water managers to adapt their decision making based on scientifically-proven streamflow forecasts.

2. *Utilizing our natural resources*
a. ensure American Energy is available to meet our security and economic needs;
b. ensure access to mineral resources, especially the critical and rare earth minerals needed for scientific, technological, or military applications;
c. refocus timber programs to embrace the entire ‘healthy forests’ lifecycle;
d. manage competition for grazing resources.

Response: Not applicable

3. ***Restoring trust with local communities***
a. Be a better neighbor with those closest to our resources by improving dialogue and relationships with persons and entities bordering our lands;
b. Expand the lines of communication with Governors, state natural resource offices, Fish and Wildlife offices, water authorities, county commissioners, Tribes, and local communities.

Response: The proposed work, specifically Aim 2, will increase and facilitate communication and cooperation with our project partners, and potentially lead to expanded communication with additional irrigation district managers in the region.

4. ***Striking a regulatory balance***
a. Reduce the administrative and regulatory burden imposed on U.S. industry and the public;
b. Ensure that Endangered Species Act decisions are based on strong science and thorough analysis.

Response: Not applicable

5. ***Modernizing our infrastructure***
a. support the White House Public/Private Partnership Initiative to modernize U.S. infrastructure;
b. remove impediments to infrastructure development and facilitate private sector efforts to construct infrastructure projects serving American needs;
c. prioritize DOI infrastructure needs to highlight: 1. construction of infrastructure,
2. cyclical maintenance, and
3. deferred maintenance.

Response: Not applicable

5. Project Budget

5.1 Funding plan and letters of funding commitment

The non-Federal portion of project costs will be provided by Oklahoma State University as a cost match using PI Ochsner's salary. A letter of funding commitment can be found below.

5.2 Budget proposal

Table 1. Total project costs

SOURCE	AMOUNT
Costs to be reimbursed with the requested Federal funding	$88,476.00
Costs to be paid by the applicant	$88,488.00
Value of third-party contributions	$0.00
TOTAL PROJECT COST	**$176,964.00**

Table 2. Budget Proposal

Budget Item Description	COMPUTATION		Quantity Type	TOTAL COST
	$/Unit	Quantity		
Salaries and Wages				
PI Ochsner	42,600.00	1	USD	42,600.00
Co-PI Wyatt	46,500.00	1	USD	46,500.00
Fringe Benefits				
PI Ochsner	16,550.00	1	USD	16,550.00
Co-PI Wyatt	9,142.00	1	USD	9,142.00
Travel				
In-state	500.00	1	USD	500.00
Out-of-state	3000.00	1	USD	3000.00
Equipment				
NA				
Supplies and Materials				
NA				
Contractual and Construction				
NA				
Third Party In-Kind Contributions				
NA				
Other				
NA				
TOTAL DIRECT COSTS				**$118,292.00**
Indirect Costs				
Agency	29,334.00	1	USD	29,458.00
Oklahoma State University	29,338.00	1	USD	29,476.00
TOTAL ESTIMATED PROJECT COSTS				**$176,964.00**

5.3 Budget Narrative

Salaries and Wages

PI Ochsner will commit 5 months to the project, a cost of $8,520.00 per month. Dr. Ochsner will be responsible for project leadership and will contribute under Aims 1 and 2 as described in the proposal. The costs associated with those contributions are included in Table 2.

One *Postdoctoral Researcher* (Co-PI Wyatt) will be hired for 12 months at a rate of $3,875.00 per month at Oklahoma State University to complete the development of streamflow forecasts as described in Aim 1 and the dissemination of those forecasts to irrigation district managers as described in Aim 2. This postdoc will be supervised by Dr. Ochsner. The costs associated with those contributions are included in Table 2.

Fringe Benefits

Fringe benefits for *PI Ochsner* are estimated to be $16,550.00, based on a FY 2020 benefit rate of 38.85%. Fringe benefits for *Co-PI Wyatt* are estimated to be $9,142.00, based on a FY 2020 benefit rate of 19.66%.

Travel

Five hundred dollars are requested to fund travel to three in-state meetings where *Co-PI Wyatt* will share results from the project with the scientific community, policy makers, and end users. This cost includes car rental at $35.00/day and mileage at $0.23/mile to travel from Stillwater, OK to Oklahoma City (132 miles round-trip, $65.00 per trip) three times, as well as registration costs of $100.00 per meeting.

Three thousand dollars are requested for out-of-state travel in order to allow *PI Ochsner* and *Co-PI Wyatt* to disseminate project findings at the 2020 Soil Science Society of America Annual International Meeting to be held in Phoenix, Arizona on November 8-11, 2020. This cost includes airfare estimated at $600.00 round trip per person, daily per diem of $146.00 for lodging and $56.00 for meals (total of $808.00 per person for four days), and $92.00 per person for miscellaneous travel expenses (taxi, baggage fees, parking fees, internet fee, etc.).

Equipment- Not Applicable

Materials and Supplies- Not Applicable

Contractual- Not Applicable

Third-Party In-Kind Contributions- Not Applicable

Environmental and Regulatory Compliance costs- Not Applicable

Other Expenses- Not Applicable

Indirect Costs

Indirect costs are calculated at a rate of 49.6%, leading to IDC totals of $29,458.00 from the Bureau's contribution of $59,392.00 and $29,476.00 from Oklahoma State University's contribution of $59,428.00.

6. Environmental and Cultural Resources Compliance

Will the proposed project impact the surrounding environment (e.g., soil [dust], air, water [quality and quantity], animal habitat)? Please briefly describe all earth-disturbing work and any work that will affect the air, water, or animal habitat in the project area. Please also explain the impacts of such work on the surrounding environment and any steps that could be taken to minimize the impacts.

Response: No, the proposed work should not impact or pose a threat to the environment. The entirety of the proposed work is computational and will not have any negative effects on the surrounding environment.

• Are you aware of any species listed or proposed to be listed as a Federal threatened or endangered species, or designated critical habitat in the project area? If so, would they be affected by any activities associated with the proposed project?

Response: While there may be species listed as threatened or endangered within the irrigation districts of interest, the completion of the proposed work would not directly affect those species.

• Are there wetlands or other surface waters inside the project boundaries that potentially fall under CWA jurisdiction as "Waters of the United States?" If so, please describe and estimate any impacts the proposed project may have.

Response: While there may be bodies of water under CWA jurisdiction within the irrigation districts of interest, the completion of the proposed work would not directly affect those areas.

• When was the water delivery system constructed?

Response: The Altus Dam was constructed in 1941-1945 and modified in 1988. The Bostwick irrigation district contains many dams, all whose construction was completed prior to 1958. The Frenchman-Cambridge irrigation district contains numerous dams, all whose construction was completed prior to 1961.

• Will the proposed project result in any modification of or effects to, individual features of an irrigation system (e.g., headgates, canals, or flumes)? If so, state when those features were constructed and describe the nature and timing of any extensive alterations or modifications to those features completed previously.

Response: No, the proposed project will not result in any modification of or effects to individual features of an irrigation system.

• Are any buildings, structures, or features in the irrigation district listed or eligible for listing on the National Register of Historic Places? A cultural resources specialist at your local Reclamation office or the State Historic Preservation Office can assist in answering this question.

Response:
There are a number of registered historical places in and surrounding the project locations (Figure 9), but the proposed project should not have an impact on these properties.

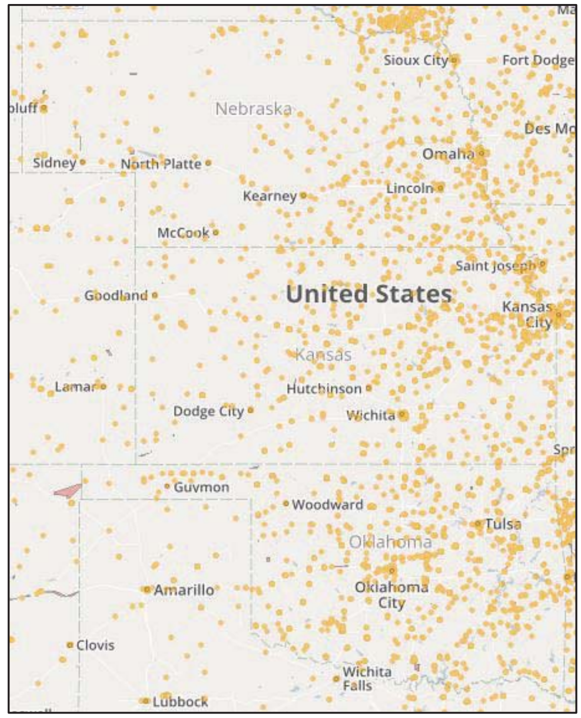

Figure 9. Locations of Historic Places in OK, KS, and NE.

• Are there any known archeological sites in the proposed project area?

Response: To the best of our knowledge, no**.**

• Will the proposed project have a disproportionately high and adverse effect on low income or minority populations?

Response: No.

• Will the proposed project limit access to and ceremonial use of Indian sacred sites or result in other impacts on tribal lands?

Response: No.

• Will the proposed project contribute to the introduction, continued existence, or spread of noxious weeds or non-native invasive species known to occur in the area?

Response: No.