Technology for trade: new tools and new rules for water use efficiency in agriculture and beyond

(a) Introduction

Irrigated agriculture accounts for roughly half of the total value of crop sales in the United States (USDA ERS 2017) and for about 70% of water withdrawals in the Western U.S. (Maupin et al. 2014), suggesting that agricultural systems and water systems are strongly interdependent (Adams et al. 2009; Barnett et al. 2008; Mendelsohn and Dinar 2003). Agricultural systems are also evolving rapidly, driven by changes in food demand (Valin et al. 2014), technology (Liu and Shumway 2009), and climate (Howden et al. 2007; Schlenker and Roberts 2009) thus driving changes in how water is used in food production and processing.

Water reallocation is increasingly important for ensuring that water resources are applied to their highest-valued uses, whether in agriculture or other competing uses (Goemans and Pritchett 2014; Marston and Cai 2016; Mendelsohn 2016). Water allocation is dependent on natural hydrology, built infrastructure for holding and moving water, demand for water across space and time, and the interests of stakeholders and claimants to apply or conserve water. Water allocation is further framed by institutions: laws, regulations, administrative processes, markets, contracts, and informal rules and norms; all of which affect incentives for water use, conservation, and investment (North 1990; Saleth and Dinar 2005; Tirole 1988). The structure of governance and institutions is in turn shaped by stakeholder incentives, information (Furubotn and Richter 2005; Nee and Ingram 1998; Ostrom et al. 2003; Randall 1981; Ruttan 2000), and characteristics of the resource (Coase 1960; Cornes and Sandler 1996; Demsetz 1974; Libecap 2007).

Water markets can be powerful tools for allocating water to high-valued uses and increasing the productive value of water. Water markets are increasing in number and transaction volume across the West (Brewer et al. 2006); however, they are currently hindered by information-related constraints and transaction costs that limit their efficacy and can even exacerbate resource misallocation relative to no market at all (Allan 1999; Carey et al. 2002; Challen 2000; Colby 1990; Easter et al. 1998; Livingston, 1993). For example, uncertainty over seasonal water availability and consumptive use can affect planting decisions, limit water leasing options and irrigation season planning, and increase transaction costs of water trades.

Many of these challenges can be mitigated with better information from emerging information technology systems. Indeed, information technology is already changing the legal and management landscape of water resources in the Western U.S. For example, improvements in groundwater modeling have led to legal challenges and a tighter connection between the legal and regulatory management of surface and groundwater rights in several western states. Culp et al. (2015) and others emphasize the importance of institutional change for more flexible and resilient water allocation systems. More generally, the evolution of governance institutions has always been framed by contemporaneous and emerging technologies, and vice-versa (Auerswald and Stefanotti 2012; Fountain 2004; Saviotti 2005).

The connections between technology and institutions is the focus of a rapidly expanding body of research in the social sciences driven by advancements in information technology (IT) in the last decade. This proposed project revolves around the central hypothesis that technology and institutions interact in important ways, and that capitalizing on complementarities between the two can lead to increased water use efficiency gains and more effective use of new technology.
Our long-term goal is to enhance water use efficiency and associated economic gains for irrigated agriculture and other water uses through improving emerging information systems and identifying complementary institutional innovations that lead to effective water markets.

To pursue this goal, we focus on emerging technologies with potential for improving allocative and technical efficiency in their own right, but also have clear potential to promote more effective water law, regulation, and contracting opportunities for moving water to its most productive and valuable uses. Our three focal emerging technologies are improved seasonal water forecasting, automated consumptive use monitoring, and “smart” markets for leasing and trading water – that can increase the technical and allocative efficiency of water consumption (see Glossary of Terms, right).

Our specific objectives are to (1) develop and/or extend the focal technologies to facilitate planning, implementation, and monitoring/enforcement for market transactions; (2) use stakeholder input to identify opportunities and scenarios for technology adoption and institutional adaptation and collect data through experiments, surveys, and other sources; and (3) test and estimate the efficacy of technology adoption and stakeholder-identified institutional adaptation for improving water use efficiencies in agriculture and competing uses.

Our testbed is the Columbia River basin (CRB), the second largest watershed in the continental U.S. The diversity of water users, storage limitations (with natural storage diminishing as snowpack decreases due to climate change), and drought risk create imposing water management challenges, but there is also potential to substantially improve system-level biophysical and economic water use efficiencies through water market improvements. Improving water markets will require implementing multiple synergistic technologies to deliver timely and targeted information to reduce regulatory, information, and transaction costs.

Our team is uniquely qualified and positioned to succeed due to its interdisciplinary expertise in biophysical modeling (Rajagopalan, Adam, Barber, Abatzoglou, Nijssen, Stöckle, Pickering, Liu), economic modeling and survey implementation (Yoder, Brady, Cook), water institutions/water rights (Young, Yoder, Cook, Brady, Padowski, Haller), and extension (Yorgey, Kruger). A substantial portion of Objective 1 and the basis for our stakeholder interactions will leverage work developed in the 2016 Columbia River Basin Long-term Water Supply and Demand Forecast project (Adam, Barber, Rajagopalan, Liu, Haller, Brady, Yoder, Padowski, Yorgey, and Kruger). In addition, this project will take advantage of modeling and case study outputs being developed by Adam, Yoder, Rajagopalan, Pickering, and Padowski through an

Glossary of Terms:

Allocative efficiency - The degree to which goods and services such as water are applied to their highest-valued use.

Technical efficiency - The effectiveness with which a given set of inputs such as water is used to produce outputs.

Water use efficiency - Refers to either or both allocative or technical efficiency, meaning the productivity or value of consumptive water use.

Irrigation efficiency - The ratio of consumptive use to the water volume applied as irrigation.

Institutions - Social rules and norms, such as law, regulation, contracts, agreements.

Water allocation system - The rules and procedures through which access to water for both consumptive and non-consumptive uses is permitted.
NSF-INFEWS award (NSF-EAR 1639458). Work improving researcher-stakeholder feedback mechanisms related to water for agriculture will also be leveraged (Kruger and Yorgey).

Long-term success hinges on actual adoption of technologies and institutional innovation. Therefore, the project will be co-developed with stakeholders to minimize barriers, disincentives, and impediments to adoption. Stakeholder engagement is tightly integrated into each of the objectives, with the aim of creating project deliverables that are pragmatic, value-added, and adoptable. Our team (particularly Yorgey, Kruger, Haller, and our External Evaluation Team) has extensive experience and expertise in stakeholder engagement.

(b) Rationale and Significance

The stated goal of the Water for Food Production Systems Challenge Area is “to sustainably increase agricultural productivity and availability of safe and nutritious food while significantly reducing water use and preserving water quality.” Achieving this goal requires using water for food production and processing more efficiently. Efficiency in this context can take two forms. The first is technical efficiency, in which production is increased per unit of water consumed. This is akin to a “more crop per drop” perspective on water use efficiency (not to be confused with irrigation efficiency). Second is economic or allocative efficiency, in which water is allocated to its highest valued use among competing alternatives, thereby maximizing the value of available water or reaching an economic goal with minimal water use (Cai et al. 2003; Griffin 2016). Technical and allocative efficiency work in tandem to maximize limited water resources (Kopp and Diewert 1982).

This RFP is targeting systems approaches to support increased agricultural production while reducing water use. We aim to develop and improve a set of specific technologies and identify synergistic institutional innovations to improve water use and allocation efficiency in agriculture; this requires a systems approach to capture the important interdependencies within and between biophysical and social-economic systems. In doing so, we integrate “efficient economic, environmental, behavioral, social, and policy approaches” as the call directs. Of the specific priorities listed in the RFP, our research falls into the following:

- Innovative ways to sustainably secure and more efficiently use water to produce food given competing resource demands, varying annual and within season availability, and compromised or limited water quality.
- Targeted activities/interventions beyond simple information delivery to overcome barriers, disincentives, and institutional or legal impediments so that more sustainable management practices are adopted and acceptance encouraged.

Our focus at the intersection of emerging technology and institutional innovation is based on a recognition that timely and accurate information for water users, regulators, and stakeholders can provide opportunities for improving technical water use efficiency (priority bullet point 1), but that institutional context affects incentives for allocative efficiency, which in turn affects water use decisions and behavior. Thus, a focus on both new technology and the institutional context is critical to incentivise decisions about the private use of shared water resources. The technologies and institutional innovations we will pursue are specifically targeted to overcome “barriers, disincentives, and institutional or legal impediments” primarily for improving
allocative efficiency in water use across competing uses and users, and for the purposes of reducing regulatory, administrative, and transaction costs (priority bullet point 2).

(c) Approach

We will pursue a set of objectives relating to three technologies that provide promise in themselves for helping to improve water use efficiency and also provide a foundation for changing the legal and regulatory landscape of water in ways that can improve water use efficiency within the agricultural sector and beyond.

The objectives of this project revolve around developing these technologies and identifying opportunities for institutional change at relevant levels of social organization to complement them and maximize their potential. While this project is limited to a five-year time span, the goal of developing tools and direction for institutional innovation will continue with a long-term goal of improving technical and allocative efficiency in water use into the future. Specific objectives below work toward that goal.

Within the CRB, we focus on three watersheds in central Washington where drought and water shortages are relatively common and severe: the Yakima Basin, Walla Walla, and the Okanogan (Figure 1). These areas of the state were chosen not only because water is scarce, variable, and in high demand, but because their water management institutions are surprisingly diverse given that they face the same statewide legal institutions surrounding water.

Our research objectives are aided by variation among the research watersheds in two dimensions: (1) curtailment (reduced water availability) frequency, and (2) transaction search and matching costs. The Yakima Basin leads the region in terms of value of production, but it is affected by drought less frequently than some other parts of the state. Our hypothesis tests are improved if we have study regions with regular curtailments as it provides a more reliable opportunity to observe trading activity. Both Okanogan and Walla Walla have irrigation water curtailed every year.

Water markets are significantly impeded by the transaction costs of finding a buyer and seller that fit all the requirements for a legal trade (search and matching costs). We posit that these costs are a function of the presence of larger water rights entities and geographic distance. Yakima is dominated by Federal irrigation districts relative to Okanogan and Walla Walla watersheds. Irrigators are spread over a larger geographic area in Okanogan as compared to Walla Walla. As we pursue our objectives, we will utilize this variation across watersheds to identify idiosyncrasies and generalities and their impacts on outcomes.

1. Objectives

Our objectives are designed to tightly integrate research with stakeholder input to develop and extend three sets of technologies for enhancing water use efficiency, identify synergies in water institutions, and test and quantify these synergies. Each objective relies on critical and necessary engagement with water stakeholders, including water users, managers, regulators, and
scientists, among others. Therefore, in this integrated Research and Extension project, we do not explicitly distinguish between Research and Extension components in each of our objectives, but do highlight where major stakeholder engagement takes place in each one (See Figure 2).

**Objective 1**: Develop and enhance a suite of technologies to catalyze water use efficiency and water market function.

**Objective 2**: Identify opportunities/scenarios for technology adoption and institutional adaptation; collect data through experiments, surveys, focus groups, and other sources.

**Objective 3**: Assess the efficacy and value of new tools and rules for better water use efficiency.

**Objective 1** focuses on developing and/or extending three technologies that show promise for market catalyzation and facilitation with which our team has unique expertise:

- **Improved seasonal water forecasting** can help farmers plan their planting and water use activities earlier and with less uncertainty. Both short term (intra-year) and long term (multi-year) decisions are made by individual producers, irrigation districts, and regulatory agencies, which affect water use and production outcomes. Irrigators must often commit to planting, contracting, and irrigation plans before the irrigation season begins. Better and earlier forecasts can provide opportunities to adjust cropping and irrigation decisions over the irrigation season on their own farm. Improved forecasting can also facilitate types of water transfers that are relatively rarely used, such as options (dry-year) contracts (Hansen et al. 2014; Rey et al. 2015), or prepare for public reverse auctions for instream flow augmentation in dry years (Cronin 2015).

- While seasonal climate forecasts are currently available at coarse spatial resolutions (e.g. North American Multi-Model Ensemble (NMME) at 1 degree resolution; Kirtman et al. 2014) with lead times of about 9 months, translation of this to forecasts of irrigation water availability and crop productivity is largely unavailable. If available, forecasts could provide critical information for producers, irrigation districts, and regulators to proactively plan for drought mitigation strategies such as initiating emergency well permits, and encouraging water market transactions that benefit irrigation and instream flow.

- **Automated consumptive use monitoring** can play several important roles in water management at the farm and regulatory level. For irrigators, it can provide information about likely impacts of deficit irrigation strategies on crop yields, which may reduce the financial harm from droughts relative to fallowing. For regulators, it can provide a basis for reducing the costs and increasing the accuracy of consumptive use to support consumptive-use-based water transactions and minimize negative third-party effects of trade and changes in use (Colby 2016; Huffaker 2016). It can also provide a low-cost means to monitor and enforce the terms of water transactions for partial water leases that allow subsequent deficit irrigation by the seller rather than requiring a full water lease and fallowing.

- **Smart markets** are computer-assisted electronic clearinghouses to facilitate transactions of goods and services. They ease the process of matching multiple sellers and buyers of water rights, and help navigate the highly complex regulatory constraints for a successful trade (McCabe et al. 1991; Murphy et al. 2000; Young and Brozovic 2016). The development of computer automated searching and matching algorithms has enabled the realization of peer-to-peer markets including eBay, Uber, and Airbnb (Cannon and Summers, 2014; Chade et al. 2017; Einav et al. 2016). These markets in turn have caused regulatory changes permitting
transactions that were previously prohibited. There is also the potential for changes in formal rules to occur, often due to a legal action, and then create incentives for technological change (Ruttan 2000). Smart software systems can be tailored to local legal, regulatory, and environmental conditions. Once established, they can help buyers and sellers understand which types of transactions are likely to be quickly approved and which may require more legal scrutiny. They can also reduce other transaction costs and sources of market frictions. Regulatory oversight can be cumbersome, but integrating formulaic administrative rules into the market infrastructure can substantially reduce compliance costs. Smart markets have been in the literature for decades, but recent advancements to commercialize smart market technology have finally led to their deployment. Mammoth Trading’s (led by Co-PI Richael Young) smart market platforms were developed from research funded by the USDA and the NSF, and are currently deployed in parts of Nebraska and Washington State.

**Objective 2** focuses on identifying opportunities for using the three focal technologies for improving water use efficiency and associated benefits. Institutions surrounding water use are complex and affect incentives for technology adoption and for pursuing water use efficiency. Therefore, it is important to understand and identify how these focal technologies interact with institutions, and how they can be adopted and adapted most effectively to improve water use efficiency and economic outcomes.

Stakeholder involvement will be critical for identifying which institutions most constrain the technical and allocative efficiency of water use and which reforms will be the most beneficial. The following are important examples relevant to our focal technologies.

1) **Catalyzing water trading and options contracts with improved water forecasts.** Earlier and more dependable seasonal water forecasts for irrigation will open up opportunities for water use and water transfers that might otherwise be missed. For example, where water storage is available, an earlier winter/spring forecast in a potential drought year may provide some early-season water users (e.g., hay growers) the information necessary to decide to lease water to late-season high-valued crops such as tree fruit or hops enterprises. Improved forecasting may also improve the performance of water options contracts. The Technology-Institution nexus in this case includes private contractual, irrigation district and storage management decisions, whereby both technical and allocative efficiency could be improved.

2) **More efficient irrigation management and trade with improved consumptive use monitoring.** More precise and lower-cost consumptive-use measurement can provide opportunities for more nimble and efficient water use, the opportunity to trade consumptive use savings, and stronger assurances that transfers will not impose negative third-party effects. For example, water leases are generally predicated on lease-fallow arrangements, but effective consumptive-use monitoring could allow more flexible deficit-irrigation arrangements to be carried out and enforced. The Technology-Institutions nexus is at the private level (developing deficit-irrigation contracts) and at the regulatory-administrative level (irrigation districts, the State), because it requires new scope for accurate monitoring and enforcement to ensure deficit irrigation by the seller. Benefits include stronger incentives to improve technical efficiency and allocative efficiency through gains from trade. The reliance of the USDA Risk Management Agency on remote sensing data for enforcing and verifying crop insurance policy claims is a precedent that this general approach is technically feasible and can be accepted by the farming community (USDA RMA 2006).
3) Implementing formulaic trading rules and multi-party trades with smart markets.
Implementing basin-specific formulaic rules for trades in smart markets can reduce the administrative costs of individual trades, but requires regulatory buy-in and approval. Similarly, bilateral trading between buyers and sellers is often difficult because volumes of water for sale versus volumes sought for purchase by buyers are often different. Smart markets maximize gains from trade among the set of buyers and sellers, which could be large or small. It may also allow sales and purchases from downstream to upstream as part of a portfolio of transactions that could provide no net increase in upstream withdrawals (to minimize the risk of third-party effects). Each of these types of changes to utilize a smart market would require administrative and/or regulatory approval to allow implementation across and within irrigation districts.

These three scenarios are examples of possible outcomes affected by technology-institutional interdependence. We rely on these three examples to illustrate our approach below, but our topical focus will ultimately be directed by stakeholder engagement. Based on early focus group meetings and surveys, we will identify opportunities and develop strategies for improving water use efficiency via these technologies.

We will then use the three technologies as the foundation for computer-based simulation exercises with stakeholder participants to examine how technologies and trading rules and other institutional factors affect outcomes, and how they might be best designed. For example, we will be carrying out water trading experiments, which will allow us to estimate the gains from trade associated with the utilization of smart markets in experimental settings. We can assess the value of improved forecasts and/or consumptive use information by varying the type of information available and examining how that affects trading constraints and outcomes.

To efficiently accommodate system complexity, we will pursue a modular modeling approach in which different combinations of models will be used for technology development (Objective 1) and for assessment (Objective 3), with model modules that can work independently, but can be integrated when appropriate, much like the focal technologies themselves. As part of Objective 2, we will develop an integrated systems-analysis model to more fully describe and understand the most important interdependencies that will guide design.

Objective 3 involves assessment of the value of technology adoption and institutional adaptations for improving water use efficiency and economic benefits. The value of technology adoption and institutional adaptation stem in part from how they affect water use incentives and behavior. If technology adoption and/or institutional change induces more efficient water use and/or water allocation, we should be able to test whether this is the case and measure the effect via various metrics of interest. The tasks in Objective 2 are designed to guide such an analysis, and generate and collate data that will allow us carry out such assessments in Objective 3.

Objective 3 begins with development of assessment models to make use of data to measure outcomes, or potential outcomes, of adoption and adaptation. Our initial short-run assessments will rely on data generated from the surveys, computer-driven experiments, and simulations implemented as part of Objective 2 and other available data. The assessment models, in the form of a secondary suite of econometric and simulation models, will then be used to assess the value of the focal technologies and institutional innovations in terms of water use efficiency and its related benefits.
2. Methods

Specific tasks are organized around the three objectives and summarized in Figure 2. Because the objectives are interdependent, some of the tasks will be carried out simultaneously, and some sequentially as summarized in the timeline near the end of the narrative.

Objective 1: Develop and enhance a suite of technologies to catalyze water use efficiency and water market function.

Tasks for Objective 1 are designed to guide and improve development of each of the focal technologies, relying on stakeholder engagement to assure that the technology developments are well-focused on critical relevant issues as identified by stakeholders.

Task 1.1: Stakeholder engagement to inform technology development.

We will engage with a diverse group of stakeholders, including irrigators, irrigation district managers, storage management decision-makers, potential buyers and sellers of water rights, drought response managers, state agencies who regulate water use and water transactions, and entities with regulatory oversight for water transactions. By interacting with these stakeholders, we will refine our understanding of the type and timing of critical information needs that could enhance stakeholder decision making and efficient allocation of water across multiple uses. Initial stakeholder engagement will include a series of focus groups (one in each focal watershed plus one targeted at those who make decisions at a regional level) to map important seasonal decision points and timing, and the critical information needs that could enhance decision making and efficient allocation of water across multiple uses. As technology development proceeds, more focused feedback will be obtained through the stakeholder advisory process (described in detail in the Management Plan), complemented as needed with workshops aimed at target user groups.

To address these challenges, our stakeholder approach emphasizes an actionable, pragmatic approach that builds towards knowledge co-production and co-dissemination (Lemos and Morehouse 2005; Mauser et al. 2013; van der Hel 2016). The approach has been built on a
decade of experience facilitating researcher-stakeholder collaborations—including irrigators, irrigation district managers, state agency representatives, environmental interests, tribes, and others—to explore issues relating to agriculture and water, as well as climate change and other topics (e.g. Adam et al. 2015; Allen et al. 2017a; Hall et al. 2016; Kruger et al. 2010; Yorgey et al., 2012). It also relies on numerous trusting relationships formed over that time period with key stakeholders in the region. Over time, the understanding developed by our team relating to the concerns and challenges that producers are facing, and how producers make decisions (Allen et al. 2014; Allen et al. 2017b), has enabled us to produce relevant tools, research, and extension that responds to their needs (Allen et al. 2016; Allen et al. 2015; Hall et al. 2016b; Rajagopalan, in development; Yorgey et al. 2016).

**Task 1.2: Develop a seasonal water availability and crop productivity forecasting system.**

The seasonal water and crop productivity forecasting model will be designed to provide improved and more timely water availability forecast metrics to facilitate water allocation decisions of producers, irrigation districts, and regulators.

**Proposed forecasting system.** We provide three seasonal forecasts with varying model and data needs, each driven by the North American Multi-Model Ensemble (NMME) climate forecasts (Kirtman et al. 2014). The first is a set of forecasts directly derived from NMME climate variables (e.g. forecasts of potential evapotranspiration (ET), snowpack information, and drought indices such as the Palmer Drought Severity Index). The second is a set of unregulated streamflow forecasts based on hydrology models driven by NMME climate forecasts. The third is a set of seasonal forecasts of water availability for irrigation and crop productivity based on coupled crop-hydrology-water management models driven by NMME climate forecasts. This enhanced forecasting system accounts for irrigation demands, instream flow requirements for fish, the systems of water rights, and water supply characteristics.

The utility of seasonal climate forecasts has been impaired by its coarse spatial resolution (1°), low forecast accuracy, and difficulty transforming data into useful metrics. PI Abatzoglou has developed a set of downscaling procedures (e.g., Wood et al. 2004) compatible with NMME seasonal forecasts that are updated monthly to provide gridded forecasts at a 4-km resolution. The downscaling procedure has been shown to provide added value over raw NMME forecasts in some regions of the western U.S. (Barbero et al. 2017).

**Descriptions of Individual Component Models.** The Variable Infiltration Capacity (VIC) model (Liang et al., 1994) is a spatially-distributed, physically-based macro-scale (resolution: 1/16th - 2°) land surface hydrology model. VIC has been evaluated and applied at global (Adam et al. 2009; Barnett et al. 2005), U.S. (Livneh et al. 2013; Maurer et al. 2002), and CRB scales (Elsner et al. 2010; Liu et al. 2013). CropSyst is a mechanistic crop growth, phenology, and management model that captures a spectrum of biological, physical, and chemical processes. CropSyst has been evaluated in multiple studies (e.g., Benli et al. 2007; Stöckle et al. 1994, 1996, 2003, 2010) regarding crop biomass and yield production, crop water use, and crop response to water deficits. MOdel for Scale Adaptive River Transport (MOSART) is a runoff routing model with a scalable framework for subgrid routing (mainly via a subnetwork channel) and between-grid routing (mainly via a channel network structure) (Li et al. 2013). For each spatial unit, surface runoff is routed from hillslopes (through overland flow) and through subsurface flow to a “tributary subnetwork” before entering the main channel. The water resources model (WM; Voisin et al. 2013) relies on generic operating rules for each reservoir; monthly release targets are estimated
from inflow, demand, and reservoir characteristics. The water rights model utilizes existing instream-flow rules and databases of water rights including priority date, purpose/place of use, appropriated water amount, and point of diversion to determine timing and magnitude of irrigation water shortages and instream flow needs.

Description of Integrated Biophysical and Water Management Framework. The integrated model framework consists of WM-CRB, MOSART, and VIC-Cropsyst—a tight integration between VIC and CropSyst. VIC-Cropsyst has been used for long-term projections of Columbia River surface water supply and demand (Adam et al. 2014; Liu et al. 2014; Stöckle et al. 2014; Yorgey et al. 2011). As WM is a generic reservoir model, it needs additional specificity for the CRB. Borrowing elements of a detailed reservoir model for the CRB ColSim (Hamlet and Lettenmaier 1999), WM-CRB will be adapted to CRB water management, and the entire integrated VIC-CropSyst-MOSART-WM model will determine curtailment (water shortages). Curtailment amounts are fed back into VIC-CropSyst to simulate the decline in irrigated crop yields for curtailed rights and create crop productivity forecasts. The framework is driven by downscaled NMME seasonal climate forecasts, gridded historical observed climate, observations of snow water equivalent (SWE), and crop distributions. Remote sensing-based ET estimates (Task 1.3) are used to verify output and calibrate models. We apply this framework over the CRB in both forecasting (for evaluating forecast skill) and hindcasting (for evaluating the value of forecasts under different conditions of water availability) modes.

Task 1.3: Develop automated consumptive-use monitoring systems to support leasing and deficit irrigation.

Actual ET is closely related to consumptive use, which is a pivotal issue for allowing reduced (deficit) irrigation in response to water shortage or to evaluate short-term water trading opportunities. Thus, ET monitoring is useful at both the irrigation district and field scales. Implementation consists of adaptation and improvement of existing satellite and other remote sensing approaches, along with computer algorithms providing ET analytics, water stress, crop biomass, crop distribution, and other information integrated into a web-based decision aid tool. Irrigation district monitoring. The basic tool to estimate actual crop evapotranspiration is METRIC (Allen et al. 2007a, 2007b), an energy balance approach using satellite images to estimate actual ET at a resolution of 30m x 30m. Estimates are based on satellite data at 16 day intervals (or more depending on cloud cover). METRIC has been tested widely in irrigated agriculture with adequate results (Allen et al. 2005; Allen et al. 2007b; Liaqat and Choi 2015; Singh and Irmak 2011).
METRIC 16-day ET predictions will be complemented with daily field weather observations to allow daily interpolation of ET and improved by frequent remote sensing overpasses using small unmanned aerial vehicle (UAV) with mounted sensors, requiring some adaptation of the METRIC approach (Chavez et al. 2008). In addition to improving METRIC ET estimates, we will develop a user-friendly web-based interface that integrates and customizes data acquisition, processing, and reporting. The improved METRIC tool will be tested at Roza Irrigation District in the Yakima Basin. The satellite-based METRIC data will be applied over the entire irrigation district, while the UAV-based METRIC implementation will be used over a smaller area and compared with the satellite-based METRIC.

Field scale monitoring. To adjust field irrigation management and adapt to changing or uncertain water supply, growers could benefit from high temporal and spatial resolution measurements of actual ET, crop water stress, and spatio-temporal estimates of water stress effects on crop growth and yield in their fields. Generalized information will be provided by irrigation district-scale ET monitoring, but crop water status can change quickly with daily fluctuations of weather and soil water status. Field-sale monitoring of ET will help fill in this data gap. The impact of water stress on crop performance will also depend on crop growth stage. A good understanding of these factors will help growers make timely, well-informed decisions to better cope with water shortages or to make within-season decisions on water trading.

Internet-based wireless sensor nodes with thermal and RGB imaging sensors and associated data acquisition, storage and transfer modules, will be distributed in the field. Each node will be optimized to cover treatment field plots, along with sensors to monitor soil water, canopy cover, canopy vigor, and real-time weather. A small field area will be fully irrigated to provide reference ET, potential and actual crop transpiration, and soil evaporation. A crop water stress index with well-watered conditions as a reference will be used to evaluate deficit irrigation effects on crop water use and productivity. This information will be linked to an Irrigation Scheduling Program, which will also provide farmer access to hourly weather data from the dense network of WSU AgWeatherNet weather stations.

Projections of crop growth response to transpiration and crop water status will be estimated using algorithms extracted from an established cropping systems model, CropSyst (Stockle et al, 2003). Our team has successfully tested these algorithms over a diverse set of dryland crops grown in regions with widely varying precipitation (Khan et al., in review).

User Interface. An easy-to-use web-based interface will complement the data-processing software to integrate 16-day METRIC measurements with daily field values. The interface will also provide on-demand reports of actual ET to growers. The software will be evaluated on two fields and over two years for accuracy, ease-of-use, and the utility for potential water trading.

Task 1.4: Develop an expanded suite of computer-aided smart water market systems to facilitate water market transactions.

We will tailor Mammoth Trading Smart Market software technology (see Objectives section) to each of the three watersheds that we focus on (Okanogan, Walla Walla, and Yakima) to reflect their unique legal and hydrological conditions. The smart-market design and implementation will be dependent on and central to the activities of Objectives 2 and 3:

1) A set of “gamified” smart market modules will act as a platform to help identify problems and solutions for water allocation and water use efficiency.
2) The smart market technology can be designed to incorporate outputs (data) from the seasonal forecast and the consumptive use monitoring, and automate their use.
3) The mature simulation games will provide some of the data to test and estimate the potential efficiency gains from technology adoption and institutional adaptation.
4) “Live” smart market analogues will be developed for real-life market transactions.

The smart market simulator and live software will be tailored to specific trading goals and identified through Objective 2 with stakeholder involvement. For example, a smart market module for options contracts (“dry-year contract”) will be developed to facilitate this kind of transaction. With tailored smart market algorithms, we will be able to test a variety of contract designs, leasing arrangements, and complexities that emerge from stakeholder involvement. In the short run for this project, the smart market software will simulate trading activity and track the distributional and aggregate gains from trade. The long run goal is that it be adopted, and adapted further as necessary, to function as the clearinghouse for actual water markets.

Task 1.5: Integration of these technologies into a systems analytic framework.

The three focal technologies each have unique and independent roles in water use efficiency improvement, but also complement each other in important ways. For example, improved consumptive use monitoring can be integrated into a smart-market algorithm to improve the effectiveness of smart market implementation, but need not be for smart market technology to provide benefits. To maximize flexibility while limiting model complexity, we will pursue a modular approach to implementing these technology advancements. Each module will be designed to promote water use efficiency as a stand-alone product, but will be designed to work together where there are promising synergies between them. Figure 3 shows the basic relationships among the three technologies and their relationship to activities and institutions.

Figure 3. Interactions between technology and institutions.
Task 1.6: Design and development of visualizations for market planning and agency support.

The seasonal forecast and the automated consumptive use monitoring technology will be integrated to create a drought planning decision tool that includes visual displays of quantitative outcomes of biophysical (e.g. curtailment rate and timing, crop yields) and economic outcomes at various levels from farm to watershed. Our guiding template are the decision tools produced by USDA for the Dairy Margin Protection Program (MPP-Dairy). Farmers can enroll in MPP-Dairy without the use of these tools, but they are made available because financial outcomes from enrolling, or not, are determined by future milk prices and feed costs. The decision tools visually present projections of “most likely” values to communicate probabilities in a way that can be used by a farmer in a decision-tree tool. In the water context, SWE is known at any given point in time. State agencies project expected water supply availability for the summer irrigation months, but they do not provide any additional information. Our market planning tool adds: (1) a range of “likely” outcomes, (2) changes in physical crop production based on customizable farm-level details including water allocation, and (3) economic outcomes after specifying a range of management outcomes.

Task 1.7: Dissemination of contributions to focal technologies

A key task is the dissemination of information about these technical innovations through peer-reviewed articles, webinars, conferences, stakeholder workshops, a project website, and other research outlets. Our extension dissemination outlets include traditional peer reviewed extension publications (e.g. Allen et al. 2015; Brady and Yoder 2013), in-person presentations, and project websites, alongside contemporary approaches including webinars, video blogs (e.g. agclimate.net and csanr.wsu.edu), as well as social media and decision-support systems, which take advantage of technology to bridge distance and provide information in an easily accessible, on-demand format (Kruger et al. 2012).

Objective 2: Identify opportunities/scenarios for technology adoption and institutional adaptation; collect data through experiments, surveys, focus groups, and other sources.

Objective 2 provides focus and guidance for the development and use of the focal technologies, for identifying institutional innovations that these new technologies allow, and to provide data for estimating the value of technology adoption and institutional innovation. We pursue this objective through dual use of the smart-market technology as a foundation for experimentation and stakeholder engagement, as an integrator of the three technologies where applicable, and a means of collecting data from smart-market simulation games.

Task 2.1: Identify critical institutional factors that interact with focal technologies.

In addition to providing information about decision-making, the focus groups discussed in Task 1.1 will be asked to brainstorm how the focal technologies could be used, and how critical institutional factors interact with the focal technologies. This includes identifying institutional factors that hinder or facilitate technology adoption, as well as potential institutional innovations the technology either allows or facilitates. Semi-structured interviews will also be used to round out the picture of institutional-technological interactions and make sure that insights from key individuals (both local/watershed level and state/federal level) are included. This process will carry through initial states of simulation game development as a means of fixing ideas among stakeholders and to allow preliminary assessment.
Task 2.2: Develop and implement simulation games to identify how users interact with technologies and institutional innovations, and test behavioral responses and outcomes.

Simulation games using the focal technologies will be conducted with participants to a) refine those scenarios further and iterate Task 3.1, and b) learn about the preferences and constraints underlying behavioral responses to these scenarios. The latter objective follows similar research in experimental economics and water markets, including studies using undergraduate subjects (Garrido 2007; Hansen et al. 2014; Murphy et al. 2000; Tisdell et al. 2004) and those utilizing actual water users (Alevy et al. 2010; Cook and Rabotyagov 2014; Cummings et al. 2004; and Zuo et al. 2016).

In particular, we will adapt the smart market software for three modes of interaction with stakeholders. First, a “gamified” version will be accessible on a website where users can run simulations of a growing season by specifying general information about a hypothetical farm they would like to simulate (type of crop and type of irrigation technology). The software generates an estimated farm budget, including the implied value per acre-foot of water, for that scenario and randomly assigns the user a position in the river basin and the seniority of their water rights. The user can either act as a buyer or a seller. The software simulates other buyers and sellers in the market, and simulates water availability using the crop forecasting model described above with historical hydrological data inputs.

The second mode of interaction is similar but adapted for group simulations. These simulation experiments can be run as in-person meetings or online. Each session is expected to involve 5-10 participants and last 3-4 hours, with laptops or simple tablets made available for participants to access the software and run the simulations.

We will use these first two modes to experimentally vary elements of the institutional environment and measure the impact of possible institutional forms on water market activity. For example, in assessing the synergy between water markets and improved water forecasting, we would vary the timing and confidence of the forecast and measure water market transactions and the total value of water. We would also plan to pursue, depending on the scenarios identified in Objective 2, answering hypotheses (among many more) such as:

- Are participants more likely to participate in markets that allow for partial leases such as split season fallowing, partial acreage fallowing, or deficit irrigation?
- Do water right valuations show an endowment effect (Kahnemann et al. 1990) so that sellers demand a higher price than they would be willing to pay as buyers?
- Does information disclosure about market-clearing prices alter market activity? What effect does price disclosure have on price dispersion or perceptions of water value?
- Are sellers who grow forage crops more likely to accept leases when payment is made in a combination of dollars and delivered forage (O’Donnell and Colby 2009, pg.7)?
- Under what conditions do water users prefer flexible market-based approaches or infrastructure-based investments (Loch et al. 2014; Yoder et al. 2016)?
- How do options payments vary as the duration between droughts varies?

The third mode will “open” the smart markets platform for actual transactions based on recruited participants’ interest. To test whether exposure to a “gamified” smart market software system improves the likelihood of using actual transactions, we will recruit participants in each
of the three study areas and randomize them into two groups. One will be given access to the “gamified” smart markets website. The second group will serve as a control, and will answer basic questions via a mail survey on attitudes towards water markets. Confidentiality of transactions and participants will be ensured as needed to ensure participation and Institutional Review Board (IRB) requirements.

There are typically few market transactions in years with adequate water supply. In the absence of drought, the team may need to focus this third mode of actual market transactions around option contracts, which must be negotiated before knowing hydrological conditions. Depending on stakeholder interest in option contracts, we have budgeted to use funding to encourage the signing of actual contracts. This would likely subsidize the option price (the amount paid upfront to seller to commit to the contract) or perhaps cover legal or administrative costs. This subsidy might also be randomly varied by the research team in order to estimate the demand schedule for contracts.

Task 2.3: Create a system-level model of technology-institutional interactions, institutional status quo, and promising institutional responses to technology adoption.

A system-level description of the technology-institutional nexus is useful for identifying barriers to adaptation, how they may be overcome in complex environments, and identifying critical system interdependencies (Eisenack et al. 2014). Each focal technology operates within institutional constraints. For instance, water trades are based on consumptive use, currently estimated using coarse approximations such as irrigation guides. Updated policies that encourage using improved data would facilitate trades and reduce third-party impacts. The systems model would be used to identify key technological-institutional interactions/relationships, and where innovations could enhance the quality and speed of information transfers and the variety and volume of water trades, etc. This integrated systems model would support Objective 1 to identify where institutional constraints and drivers affect technology use, and would serve as a baseline framework from which Objective 3 could identify where deficiencies in current policies exist within the system to aid in scenario development.

Task 2.4. Generate and organize data from Task 2.1 and 2.2 activities to provide the foundation for Objective 3 measurement and testing activities.

Data and information from Tasks 2.1 and 2.2 will be in various forms, including survey data, open-ended narratives from focus groups, data from other primary and secondary sources, and data generated via the simulation games and experiments. These data will be organized and archived for effective use in Objective 3. See the Data Management Plan for more detail.

Task 2.5: Dissemination of results, processes, and lessons learned.

The tasks to be carried out in Objective 2 represent rich opportunities for researchers and stakeholders to learn about the issues and opportunities central to the goal of this project. While Objective 2 provides critical information for successfully pursuing Objective 3, the results, processes, and lessons learned through Objective 2 activities will be disseminated as stand-alone products as well, using outlets as described in Task 1.7.
Objective 3: Assess the efficacy and value of new tools and rules for better water use efficiency.

Objective 3 is designed to measure and test the efficacy and value of the three technologies and institutional changes. To complete this objective, we will develop and apply econometric and simulation models to the scenarios and data developed and collected in Objective 2. This process will integrate modeling modules relating to the three technologies based on needs dictated by the scenarios developed with stakeholder input under Objective 2.

Task 3.1: Develop modeling platforms to measure impact and value of technology and institutional innovations.

Integrated technology-institutional scenarios will be developed with stakeholders in Objective 2. Using a set of biophysical (see Task 1.2 for model descriptions) and economic models, we will estimate the efficiency of water use and total economic value created from limited water supplies, with and without any institutional changes. Because we will rely heavily on stakeholder input to develop these scenarios, we cannot know in advance which potential synergies water users and managers will find most compelling. Nevertheless, for illustration consider the example from the Objective 2 discussion about the use of earlier and more informative water availability forecasting as our focal technology. Currently, the Yakima Basin Project (YBP) sets curtailments during droughts in part on an assumption that future precipitation for the season will be that of an average year. This is a convenient assumption, but a seasonal water forecast would provide earlier and more precise short-run water availability forecasts. Implementation of this forecast at the basin level would require a rule change at the YBP, but farmers would likely find the forecast useful for their irrigation decisions regardless of whether the forecast were adopted at the basin management level.

Task 3.2: Testing and measuring the value of technology adoption and institutional innovation on water use efficiency and economic impacts.

Data and information generated under Objective 2 provides a foundation for assessing the value of technology and institutional innovations identified there. Depending on the scenarios identified, survey data, simulation data, and context from focus groups and the existing literature will be the basis of econometric models and assessment simulations. Yoder et al. (2016) provides one example of a benefit-cost analysis for the adoption of both supplemental water storage and markets in the Yakima Basin accounting for interdependencies between them, and is based on econometric and simulation approaches similar to those proposed here.

Task 3.3: Dissemination of results

Results from Objective 3 represent the culmination of Objectives 1 and 2 activities. Dissemination will occur through the same avenues and media as described in Task 1.7.

3. Outputs and outcomes

Outputs and outcomes are detailed in the Logic Model. Project outputs will include technology developments, data outputs, web-based visualizations, and dissemination outputs (e.g. journal and extension publications, webinars, blog posts, etc.). Key short-term outcomes include improved knowledge about a) More/less impactful technological and institutional strategies for improving water use efficiencies across agricultural and competing uses, and how
this varies across 3 watershed study areas with different contexts b) Institutional barriers and opportunities related to the adoption of focal technologies, and c) Stakeholder preferences and behaviors relating to water market activity. Over the medium to long-term, we hope that these changes result in increased adoption of the focal technologies and related institutional changes, and improved water allocation within the agricultural sector and across competing uses. The project also has the potential to improve water use allocation across the western U.S. through tools and knowledge that can be adapted to other areas.

4. Potential Pitfalls and Limitations

Our team has extensive experience working through modeling challenges, and foresee these occurring as a matter of course. However, modeled results are only as accurate as the data used to drive them. Therefore, we prioritize efforts to collect new location-specific data over the study areas. In the event that the data limit simulation accuracy and precision, we will analyze and interpret the model results based on the data uncertainties and biases. If needed, we will run stochastic simulations around distributions of uncertain parameters for interpretation.

Data collected through simulation games and surveys are critical to project success. Attracting large enough participant pools could be a bottleneck. We minimize this risk by utilizing our existing stakeholder relationships to help solicit participation and have budgeted for monetary incentives to encourage stakeholder participation. Additionally, trust is a critical factor key to engagement in market simulations. Mammoth Trading (co-PI Young is a founder) is a private enterprise with an existing market system that participants trust. By building our simulation interfaces around this existing system, we will leverage this existing trust.

It is often difficult to achieve true integration between Research and Extension activities. We proactively address this by tightly integrating Extension components into each of the objectives, rather than treat Research and Extension as independent activities.

5. External Evaluation

Comprehensive program evaluation will be an essential part this AFRI WFPS project. Evaluation is built on the project logic model, focusing on project activities, outputs, and outcomes. The evaluation plan includes formative evaluation to assess performance and provide feedback to improve the project, and summative evaluation to assess and document project impacts and outcomes. The external evaluation will be conducted by Kansas State University’s Office of Educational Innovation and Evaluation (OEIE) in collaboration with the Project Director and stakeholders; internal evaluation will be conducted by Washington State University’s Center for Sustaining Agriculture and Natural Resources (CSANR). We will leverage the expertise of CSANR who will focus on local context, facilitation, and networking, while OEIE will serve as the external lens for project implementation and delivery. OEIE has extensive experience in evaluation design and assessment, and has completed program evaluations for state and federally funded projects, including many USDA projects that integrate research and extension (see http://oeie.ksu.edu/).

Evaluation methods will be designed to address the activities, goals, and anticipated outcomes of the project and will be guided by the evaluation plan matrix that identifies the milestones, indicators, and methods for project objectives. Tools for assessing such questions will include focus groups and/or web-based surveys incorporating the Tailored Design Method (Dillman 2014; Krueger and Casey 2015) approach to effective qualitative research. Social
Network analysis (Durland 2006) descriptive statistics and content analysis will be conducted for data analysis. Evaluation strategies will include methods that utilize multiple evaluation approaches, draw on both qualitative and quantitative methodologies, and triangulate data for more robust findings where possible. Overarching evaluation questions may include:

- How has the project contributed to improving water use efficiency?
- How were results of research integrated into extension and outreach components?
- To what extent were project activities/outputs completed on schedule?
- To what extent have stakeholders adopted new technologies?
- What institutional changes have happened as a result of this project?
- To what extent did outreach successfully reach target audiences and change behavior?

The OEIE will collaborate with project leadership to develop a detailed timeline to identify milestones, which includes completion of each output and benchmark. OEIE will secure KSU Institutional Review Board approval for all evaluation activities involving human subjects. Evaluation indicators and methodologies will include inventory/review of project records, research findings, resulting recommendations, publications, other media; focus groups; surveys of project leadership, participants/collaborators, and stakeholders; project integration assessment, participant feedback; and document review and analysis of data collected by the project team.

### 6. Project Timetable

Table 1. Schedule of Activities and Milestones. * denotes a milestone (completion of a task).

<table>
<thead>
<tr>
<th>Obj/Task</th>
<th>Task description</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
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Bibliography & References Cited


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Stoeckle, C.O., Kemanian, A.R., Nelson, R.L., Adam, J.C., Sommer, R., Carlson, B., 2014. CropSyst model evolution: From field to regional to global scales and from research to
doi:10.1016/j.envsoft.2014.09.006


Bibliography & References Cited


Key Personnel Roles

Jonathan Yoder – Lead PI (40% Research; 30% Extension, 30% Management) is Director of the Water Research Center (WRC) and specializes in water resource economics. He will lead the project as a whole, co-lead Objectives 2 and 3, and co-advise PhD Student #1.

John Abatzoglou – Co-PI, sub-contract (90% Research; 10% Extension) is a climate modeler specializing in downscaling regional climate forecasts. He will contribute to Objective 1 and supervise a Programmer/Research Associate.

Jennifer Adam – Co-PI (50% Research; 40% Extension, 10% Management) is Associate Director of the WRC and hydrologist who specializes in water and crop modeling. She will co-lead Objectives 1 and 3, supervise PhD Student #2, and serve on the Management team.

Michael Barber – Co-PI, sub-contract (90% Research; 10% Extension) is a hydrologist specializing in water management. He will contribute to Objective 1 and supervise PhD Student #4.

Michael Brady – Co-PI (40% Research; 60% Extension) is a research/extension economist with expertise in economic modeling. He will contribute to all Objectives, and co-advise PhD Student #1.

Joseph Cook – Co-PI (50% Research; 40% Extension, 10% Management) is a research economist with expertise in non-market valuation and economic surveying. He will co-lead Objectives 2 and 3, co-advise PhD Student #1, and serve on the Management Team.

Daniel Haller – Co-PI, sub-contract (100% Extension) is an environmental consultant specializing in water rights permitting and water resource management. He will contribute to Objective 2 and act as a liaison to stakeholders and public agencies.

Lav Khot – Co-PI (90% Research; 10% Extension) is an agricultural engineer specializing in remote sensing and precision agriculture design. He will contribute to Objective 1.

Chad Kruger – Co-PI (100% Extension) is Director of the Center for Sustaining Agriculture & Natural Resources (CSANR) and Extension faculty. He will contribute to Objective 2 and serve on the Project Advisory Committee and Project Evaluation team.

Mingliang Liu – Co-PI (90% Research; 10% Extension) has expertise in remote sensing, crop modeling, and GIS. He holds a split appointment between Civil and Environmental Engineering and Biological Systems Engineering. He will contribute to Objectives 1 and 3.

Bart Nijssen – Co-PI, sub-contract (90% Research; 10% Extension) is a hydrologist specializing in remote sensing and hydrologic/climate forecasting. He will contribute to Objective 1 and supervise PhD Student #5.

Julie Padowski – Co-PI (40% Research; 30% Extension, 30% Management) is a water resources scientist with expertise focused on water institutions and management. She will contribute to Objective 2 and serve on the Administrative and Management Teams.

Troy Peters – Co-PI (90% Research; 10% Extension) is an agricultural engineer specializing in deficit irrigation, crop water use estimation, and irrigation decision support systems. He will contribute to Objective 1.

Nigel Pickering – Co-PI (80% Research; 10% Extension, 10% Management) is a hydrologist with expertise on modeling crop response to climate change. He will contribute to Objective 1 and serve on the Administrative and Management Teams.

Kirti Rajagopalan – Co-PI (40% Research; 30% Extension, 30% Management) specializes in water and crop modeling. She will co-lead Objective 1, contribute to Objectives 2 and 3, supervise PhD Student #3 and programmer #1, function as liaison between economic and biophysical modeling groups, and serve on the Management Team.

Cynthia Schuman – Co-PI (100% Extension) will lead the external Project Evaluation team and supervise the design and implementation of an external evaluation plan in coordination with the project director.
Claudio Stöckle – Co-PI (90% Research; 10% Extension) is a crop systems modeler focusing on crop water use at multiple scales. He will contribute to Objectives 1 and 3 and supervise a Post-Doc/Research Associate.

Georgine Yorgey – Co-PI (100% Extension) is Associate Director of CSANR with expertise in Extension aspects. She will contribute to Objective 2, facilitate stakeholder engagement, coordinate the Project Advisory Committee, and serve on the Project Evaluation team.

Richael Young – Co-PI (50% Research; 50% Extension) specializes in smart market development and implementation for water trading. She will contribute to all Objectives and supervise a Programmer.

Sonia Hall – (100% Extension) is a research associate with CSANR. She will develop extension and outreach materials for the project and help facilitate workshops and other avenues for stakeholder engagement.

Roger Nelson – (90% Research; 10% Extension) is a computer scientist specializing in crop systems modeling. He will contribute to Objective 1.

Programmer/Research Associate #1 – (100% Extension) will be hired through CSANR to develop durable web-based interactive visualizations for stakeholder engagement and outreach.

Programmer/Research Associate #2 – (90% Research; 10% Extension) will be hired by John Abatzoglou to develop statistically downscaled seasonal weather forecasts and perform skill evaluation for seasonal forecasts and hind casts for Objective 1.

Programmer – (50% Research, 50% Extension) will be hired by Richael Young to implement smart market functionality as well user interfaces for simulation games.

Post-Doc/Research Associate – (90% Research; 10% Extension) will be hired in Biological Systems Engineering to develop consumptive use monitoring systems for Objective 1.

PhD Student #1 – (90% Research; 10% Extension) will be hired in the School of Economic Sciences to develop economic models and analyze survey and simulation game results for Objectives 2 and 3.

PhD Student #2 – (90% Research; 10% Extension) will be hired in Civil and Environmental Engineering to modify coupled crop-hydrology modeling frameworks to work with seasonal weather forecasts, and develop seasonal crop productivity forecasting systems for Objectives 1 and 3.

PhD Student #3 – (90% Research; 10% Extension) will be hired in Civil and Environmental Engineering to develop forecasting systems for seasonal irrigation water availability, irrigation water shortages, and instream flow shortages for Objectives 1 and 3.

PhD Student #4 – (90% Research; 10% Extension) will be hired by Michael Barber to develop automated consumptive use monitoring systems as part of Objective 1.

PhD Student #5 – (90% Research; 10% Extension) will be hired by Bart Nijssen to develop streamflow forecasts for Objectives 1 and 3.