RECLAMATION

Managing Water in the West

Evaluating future Agricultural Water Needs using Integrated Modeling Methods

Research and Development Office
Science and Technology Program
Final Report ST-2017-1588-01

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Research and Development Office **April 2017**

Mission Statements

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The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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14. ABSTRACT *(Maximum 200 words)* Irrigated agriculture comprises the largest consumptive use of water in the Western United States (U.S.). Thus, understanding the factors that contribute to changes in agricultural water needs is essential to ensuring that water resources can be sustainably managed in the future. This study developed an agent based model that represented the behavior of three agent types, Districts, Farms, and Crops, that work together to determine the amount of agricultural water needed for a basin. The model was able to estimate the amount of agricultural water needed within nine percent of historical volumes. For simulations that consider future climate conditions, the model indicated the need for less water over time due to crop mix and land use changes.

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(Final Report) ST-2017-1588 01

Evaluating Future Agricultural Water Needs using Integrated Modeling Methods

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Executive Summary

Irrigated agriculture comprises the largest consumptive use of water in the Western United States (U.S.). Thus, understanding the factors that contribute to changes in agricultural water needs is essential to ensuring that water resources can be sustainably managed in the future.

This study used data from the Boise Valley to develop an agent based model that represented the behavior of three agent types, Districts, Farms, and Crops. These agents work together to determine the amount of agricultural water needed for a basin. The agents consider the amount of water needed, the cost to grow, and the price received of individual crop types. In addition, the type of water (natural flow, water stored in a reservoir, rented water, or groundwater) and quantity available to each farm was considered. The model was able to estimate the amount of agricultural water needed within nine percent of historical volumes.

The model was used to simulate future conditions by adjusting the amount of water needed for each crop type as a result of changing climate conditions. For simulations that consider future climate conditions, the model indicated the need for less water over time due to crop mix and land use changes.

This study followed from the Science and Technology scoping study “Scoping Methods for Evaluating and computing Future Agricultural Water Needs,” 2014.0596, and resulted in a dissertation by the principle investigator. The full document is attached.

Since this study focused on data from the Boise Valley, the next logical step would be to test the methodology in another basin. This may involve modifications to the approach and methodology to accommodate conditions in the chosen basin.

Evaluating Future Agricultural Water Needs using Integrated Modeling Methods

A Dissertation

Presented in Partial Fulfillment of the Requirements for the

Degree of Doctorate of Philosophy

with a

Major in Water Resources

in the

College of Graduate Studies

University of Idaho

by

Jennifer M. Johnson

Major Professor: John C. Tracy, Ph.D.

Committee Members: Alejandro Flores, Ph.D.; Justin Huntington, Ph.D;

Phillip Watson, Ph.D.

Department Administrator: Robert Heinse, Ph.D.

December 2016

AUTHORIZATION to SUBMIT DISSERTATION

This dissertation of Jennifer M. Johnson, submitted for the degree of Doctorate of Philosophy with a Major in Water Resources and titled "Evaluating Future Agricultural Water Needs using Integrated Modeling Methods," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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John C. Tracy, Ph.D.

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ABSTRACT

Irrigated agriculture comprises the largest consumptive use of water in the Western United States (U.S.). Thus, understanding the factors that contribute to changes in agricultural water needs is essential to ensuring that water resources can be sustainably managed in the future. This study developed an agent based model that represented the behavior of three agent types, Districts, Farms, and Crops, that work together to determine the amount of agricultural water needed for a basin. The model was able to estimate the amount of agricultural water needed within nine percent of historical volumes. For simulations that consider future climate conditions, the model indicated the need for less water over time due to crop mix and land use changes.

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Thank you to the Bureau of Reclamation's Science and Technology Program for funding to support this research. Also, thank you to my committee members, Dr. Flores, Dr. Huntington, and Dr. Watson, for their time and insight into this project. Specifically, thanks to my major professor, Dr. Tracy, for the many hours spent discussing potential concepts and reviewing methodology.

DEDICATION

Thank you to the many people who have supported me along the way particularly family, friends, instructors, and mentors. The biggest thanks goes to my husband, Cory, for his constant love and support as I pursue my goals.

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CHAPTER 1: INTRODUCTION

The arid and semi-arid Western U.S. developed primarily with the introduction of irrigated farming practices. Early settlers set up homesteads near rivers, where they could divert water from rivers and use it to irrigate crops. As the need for water grew, dams were constructed to control the timing and quantity of water in the rivers so that farmers could get the most out of the available resource. This was particularly important in the Western U.S. where farmers could not rely upon precipitation to grow crops.

Farmers today largely operate as a business and must use many factors to make decisions about the types of crops to grow. Some of the factors are fixed, such as the location of the farm and soil quality. Many of the factors vary over time at various time scales, such as the cost to grow a particular crop and the price at which the crop can be sold, the amount of water that will be available in a particular year, and the irrigation water needs of a crop influenced by weather. There are many nuances with each of these factors, and they are often interrelated.

The complexity of the irrigated agriculture system can make it difficult to determine the potential need for water under various conditions in the future. This research develops a new approach that compiles these factors into a predictive model that can be used to test how the need for irrigation water may change in the future.

Agricultural Water Needs Definition

Agricultural water needs (sometimes referred to as water demand) is a generic term to describe the amount of water that is needed to grow crops for agricultural productions. It can be interpreted conservatively to include only the quantity of water necessary for maximum growth potential of a particular crop (excluding conveyance losses), or interpreted to include the total amount of water diverted from a stream, or pumped from an aquifer. This study is focused on the conservative interpretation; recognizing that application of these values in water management modeling exercises will require additional work to account for basin infrastructure characteristics.

Water demand is distinguished from economic demand in that economic demand is a principle that describes the willingness to pay for a specific good or service. When mentioned in this study, demand refers to the demand for water which is based on the physical needs of the crops that are being grown.

Review of Previous Approaches Used to Estimate Irrigation Water Needs in the Western US[1]

As the primary supplier of irrigation water in the Western US, the Bureau of Reclamation has used multiple methods to evaluate future agricultural water needs in studies that attempt to quantify the impacts of climate change on regulated river systems.

Agricultural water needs have been considered to varying degrees in previous Reclamation studies that attempted to quantify the impacts of climate change on regulated river systems. Approaches have ranged from using water needs that represent current conditions, to using estimates that account for the potential change in water needs due to projected climatic changes. The following Reclamation studies illustrate the various methods that have been used to date:

- The River Management Joint Operating Committee (RMJOC) Climate Change study in the Pacific Northwest used a pattern volume of water needs representative of wet,

[1] Portions of this section are excerpts from a preliminary investigation conducted by the author (Reclamation 2015) and are presented here for completeness.

median, and dry conditions for the last ten years of record (Reclamation, 2011a). Use of conditions-based volume of water demand patterns in modeling allows the time series of values to change automatically during model runtime in response to changing basin conditions (wet, median, or dry - depending on projected inflows and in some cases carry-over storage). This study essentially extrapolated this functionality, and used the conditions-based volume patterns to estimate the demands that may occur as a result of climate change. This study did not account for potential changes to land use or crop distribution that could occur due to climate change which may significantly alter volume patterns. Modeling the system in this fashion allowed for an estimate of diversion shortages based on current needs; i.e. diversion shortages were quantified given the assumption that water needs remained similar to those of the last ten years, while inflows changed due to climatic shifts in temperature and precipitation. Because this study did not account for the changes to water needs that are likely to result from climate change impacts on land use and crop distribution, it was therefore limited in its ability to estimate total water availability and delivery as a result of climate change.

- The WaterSMART Basin Studies are intended to evaluate and address the impacts of climate change at a basin scale. Under the Basin Studies, current and future projected supply and water demand are evaluated. Various methods were used to quantify projected future agricultural needs in the five basin studies that have been published as of August 2014 (Colorado River, Lower Rio Grande, Milk-St. Mary's, Santa Ana Watershed, and Yakima); ranging from complex land use models to determine possible changes in irrigated acres, to simple estimates of possible percentage increase or decrease in water needs (CWCB, 2011; DBSA, 2005; DBSA, 2008; DWR, 2001; MRCOG, 2001; Reclamation, 2003-2009; Reclamation, 2011b; Reclamation, 2012a; Reclamation, 2012b; Reclamation, 2012c; Reclamation, 2013a; Reclamation, 2013c; RGRWPG, 2010; SSPA, 2000; TWDB, 2012). Although the more complex methods accounted for irrigated lands going into or out of production, only one of the studies accounted for changing crop types due to a changing climate although the methods were not explicitly described (SWWRC, 2001). In general, the estimates of future water needs in these studies were limited by current estimates of crop distribution and land use, which are likely to adjust with climate change.

- The Hood River Basin Study (Reclamation, 2014a) estimated changes in water demands by increasing the volume of water needs by ten percent per one degree Celsius (°C) increase in temperature. This factor was derived from a study conducted at Oregon State University of Agricultural Sciences on the impacts of climate change on agriculture in Oregon (Coakley et al., 2010). This increase in water needs was based only on projected temperature changes and did not account for changes in precipitation. The benefit of this method is that a possibly more accurate estimate of total water supply is attained through the modeling process because some accounting is made for additional water needs. The limitation of this method is that the change to precipitation is not considered in this estimate of volumetric water need change and similar to the method used in the RMJOC study, this method assumes that land use and crop distribution remains similar to current conditions.

- The Desert Research Institute (DRI) and Reclamation developed future irrigation demand estimates for eight major river basins in the Western US by quantifying the crop water requirement using an evapotranspiration (ET) calculator (Huntington, 2015). The demand estimates were quantified at the hydrologic unit code eight (HUC 8) scale and assumed current land use and crop distribution. The methodology used in this study was developed to understand, at a very broad scale, the potential for change in demands under three climate projections. Use of a sophisticated ET model enabled this study to account for potential changes in both temperature and precipitation. The limitation of this method lies in its assumption of current land use and crop distribution. Under such an assumption it does not fully account for changes that will likely occur under climate change.

The Idaho Water Resources Board investigated future agricultural and domestic water needs for the Boise Valley in 2010 for the Comprehensive Aquifer Management Plan (CAMP) study (WRIME, 2010). Agricultural water needs were estimated using an estimate of projected land use and crop distribution in ten year increments through 2060. Crop distribution was projected by scaling current percent distribution of crop types to projected changes in irrigated acres, and then ET was estimated using historical climate data. Total agricultural water need was adjusted for estimated conveyance and on-farm losses. No attempt was made at adjusting crop distribution for potential changes in climate, and ET was not calculated using projected climate data.

In general, the previous methods used to develop future agricultural water needs focus on the physical need for water by a defined set of crops, but assume the current cropping patterns will remain relatively unchanged. ET rates are variable depending on the crop type along with weather conditions, so the potential for crop distribution to impact water needs is likely. In addition, the change of land use from agricultural production to developed land will reduce the amount of irrigation water required since water use is a driving factor in water needs.

Many factors will likely influence the need for agricultural water including economics, legal constraints (water rights), increasing populations, and land use change. The outlook for future agricultural water needs could look drastically different than what currently exists, and yet, the current methods do not account for the factors that would indicate potentially large shifts in the volume of water needs.

Study Objective

The objective of this study is to develop a method that combines economic, social, and physical factors into a framework that can estimate future irrigated agricultural water needs. The framework will be developed using in an Agent Based Model (ABM) platform since ABMs are flexible platforms that allow for simple integration of multiple factors and the simulation of behaviors and relationships that cannot be easily simulated in other platforms.

CHAPTER 2: STUDY AREA - BOISE RIVER BASIN

The Boise River Basin in southwest Idaho was chosen as the test basin to test the hypothesis and develop the relationships necessary to form the basis of the conceptual and agent-based models (Figure 1). This basin was chosen because it is a classic representation of a regulated river system where the primary use of water is for irrigated agriculture. In addition, there are robust water datasets and computer models that can be used to determine the availability and distribution of water for varying purposes. The basin is also at an elevation that makes it likely to be impacted by potential future climate conditions.

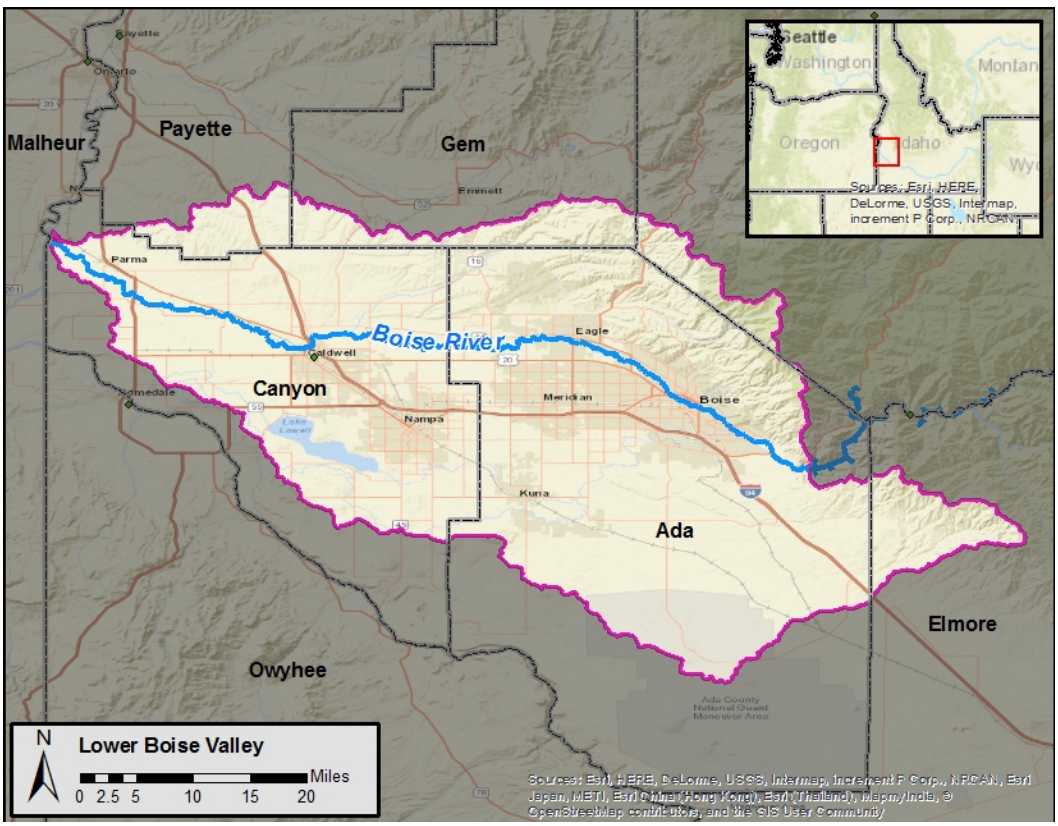

Figure 1: Project area: Lower Boise Valley HUC-8.

The Boise River flows through the Basin and drains 4,020 square miles, covering elevations ranging from 2,185 to 10,174 feet above mean sea level.

Historical Climate

The Boise River Basin climate is semi-arid, typical of high desert climates (NOAA, 2016a). The hottest month is typically July with temperatures ranging from 56 to 88 degrees Fahrenheit. The coldest months are typically December and January with average temperatures range from 22 to 36 degrees Fahrenheit (WRCC, 2016).

Figure 2 shows historical temperature range for the Boise Valley generated from NOAA data for the years 1940 through 2016 (NOAA, 2016b). The plot shows the 20, 50 (median), and 80 percent exceedance values for each month. For example, 80 percent of the average monthly temperatures in February are greater than 34, 50 percent are greater than 37, and 20 percent are greater than 39 degrees Fahrenheit.

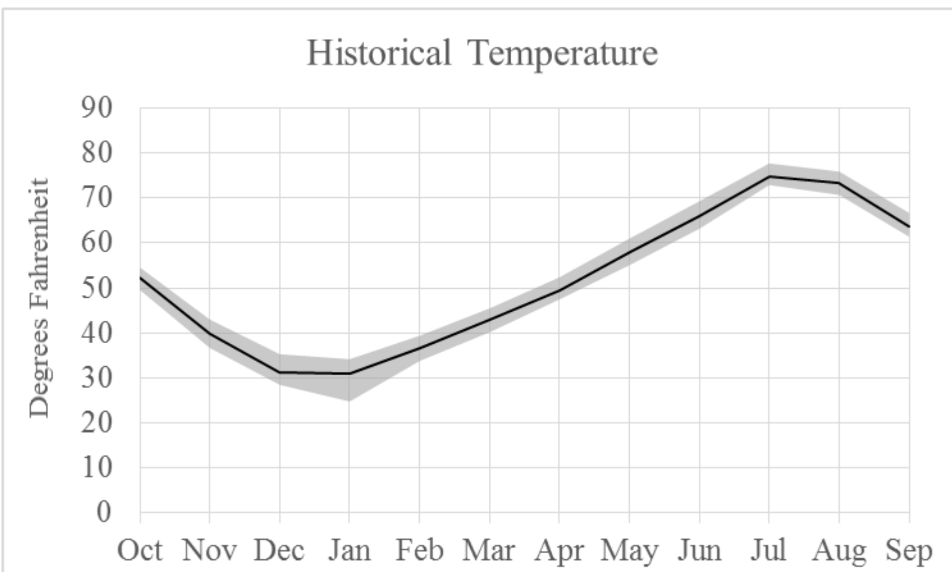

Figure 2: Historical average temperatures for the Boise Valley as measured at the Boise Airport, median (black line) and 20 to 80 percent range (grey shaded area).

Precipitation has historically ranged from about 6.5 to 17 inches per year, with the majority of precipitation occurring as snow in the winter months (NOAA, 2016b). Figure 3 shows the historical average monthly precipitation range generated from NOAA data for the years 1940 to 2015 (NOAA, 2016b). The 50 percent exceedance (median) is shown with a black line and the grey box represents the 20 to 80 percent exceedance range for each month. For example, 80 percent of the average monthly precipitation depths are greater than 0.5, 50 percent are greater than 1.0, and 20 percent are greater than 1.5 inches.

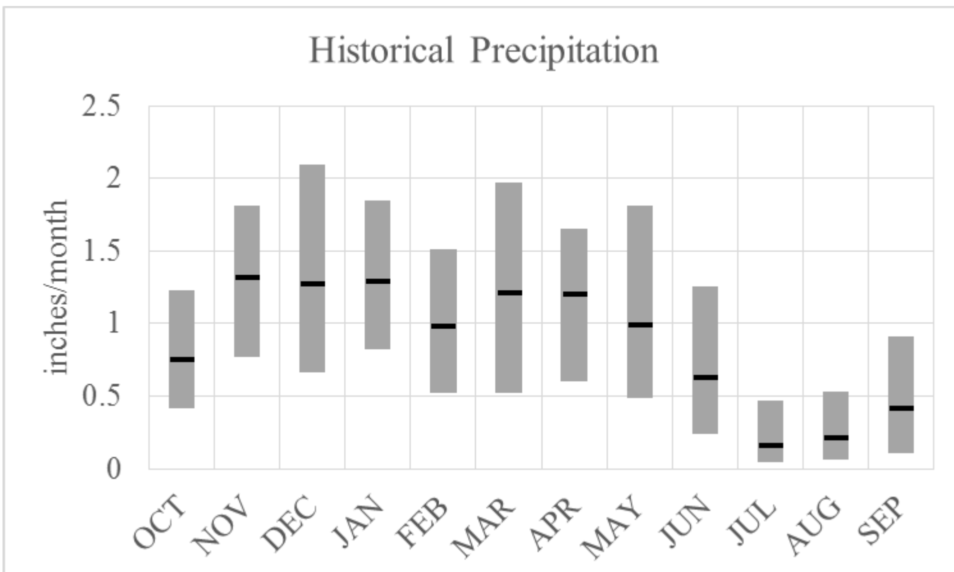

Figure 3: Historical month precipitation totals for the Boise Valley as measured at the Boise Airport, median (black line) and 20 to 80 percent range (grey box).

Hydrology

The climate and weather patterns contribute to hydrology that is typical in the arid and semi-arid regions of the Pacific Northwest, where peak river flows occur in the spring and early summer and low flows occur in the late summer and fall. Figure 4 shows in the unregulated summary hydrograph of the Boise River for the years 1980 through 2010. The hydrograph indicates that historical peak flows typically occur in May and June as the temperatures begin to warm and mountain snow melts. Towards the late summer and through the winter, the natural flows in the river are low. Flood stage on the Boise River is 7,000[2] cfs at the Glenwood Bridge gage, and this graph indicates unregulated flows exceed this value in 50 percent of the years.

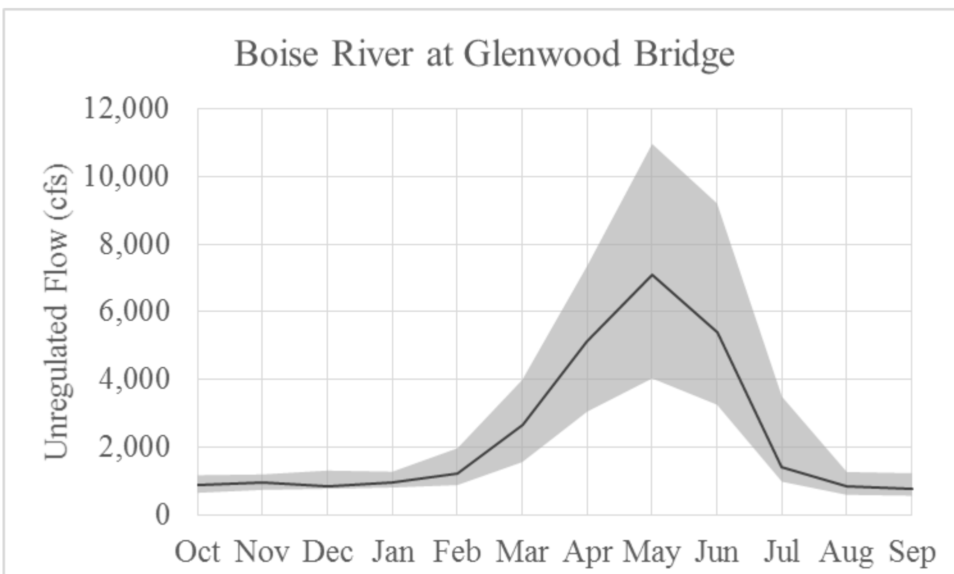

Figure 4: Unregulated average monthly flow at the Boise River at Glenwood Bridge gage; median (black line) 20 to 80 percent range (grey shaded area).

Unregulated flows are calculated flows that would occur without river management[3] and are often used as a surrogate for natural flows in a basin. Unregulated flows are used in studies of

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[2] Revised from Final submitted version which was 6,500 cfs, which is bank full.
[3] River management activities typically include storing water in reservoirs and diverting water from the river.

potential future hydrology since they are more directly related to climate and weather patterns and changes in runoff can be directly calculated using hydrology models and future estimates of weather conditions. A summary hydrograph shows the exceedance values for each month, in this case the 20, 50 (median), and 80 percent exceedance flows.

River Management

The unregulated hydrograph is altered by management of the river mainly through reservoir operation and diverting water from the river, and potentially by pumpage of groundwater from the alluvial aquifer that is hydraulically connected to the Boise River. Three reservoirs on the Boise River, Anderson Ranch, Arrowrock, and Lucky Peak, serve multiple purposes. They allow water managers to store water in the reservoirs, which helps reduce flood risk downstream of the reservoirs during periods of high natural flow. They also allows water managers to release water from the reservoirs later in the year when natural flow has decreased. This water can be released to satisfy irrigation needs or to support aquatic habitat. The reservoirs themselves are also used for recreation including boating and fishing.

Figure 5 shows the regulated summary hydrograph at the Boise River at Glenwood Bridge gage. This altered hydrograph reflects the impact of storing water in reservoir through the winter and during the spring runoff to reduce peak flows below flood stage. It also shows the increase in late summer flows that are released from the reservoirs to support irrigation. Generally, the regulation of the system allows for a more reliable water supply and reduces the potential of flooding through the more populated parts of the Basin.

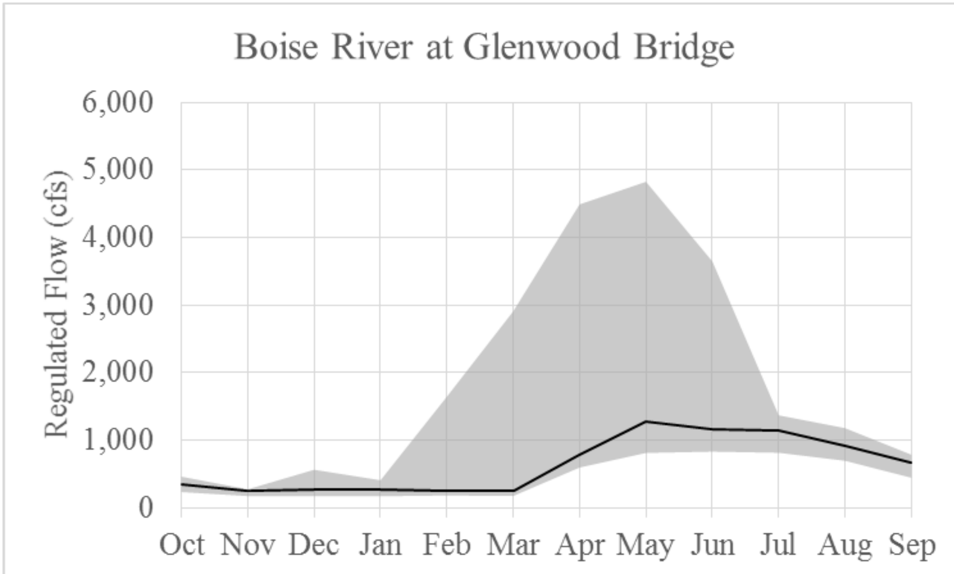


Figure 5: Regulated average monthly flow at the Boise River at Glenwood Bridge gage; median (black line) and 20 to 80 percent range (grey shaded area).

The distribution of water in support of irrigated agriculture follows a complex system of storage in reservoirs and aquifers and delivery. Figure 6 is a conceptual model of a regulated river system that is typical in the Western U.S. (from Reclamation, 2014b).

The system is comprised of elements that can store water such as the atmosphere, reservoir, shallow and deep aquifers, elements that can transport water, such as the river, drain and conveyance systems, and elements that can use water such as domestic users and farms. The elements are interconnected by many different processes, so changes to one element or process can ripple through the system in sometimes unexpected ways.

This simplified representation of the system can be used to understand the interconnectedness of individual aspects of the system. As a simple example, consider the impact of reducing on-farm infiltration by changing a farm from flood irrigation to sprinkler irrigation. Reducing on-farm infiltration would reduce the amount of water in the shallow aquifer and potentially the deep aquifer. A reduction in aquifer storage and elevation would reduce the amount of return flow to drains and the river which would reduce drain and river flow. This would reduce the amount of water available for diversion from the drains or the river downstream. It would also reduce the amount of in-stream flows for aquatic habitat.

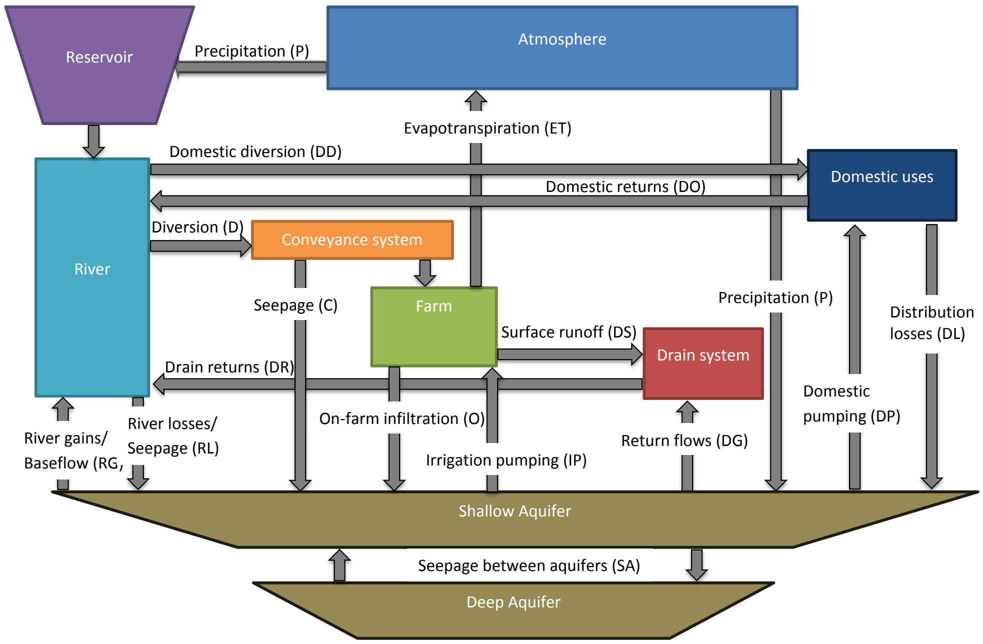


Figure 6: Conceptual representation of regulated river system (from Reclamation 2014).

River systems in the Western U.S. are regulated by state water law. In Idaho, the state constitution established natural flow water rights, the right to divert and appropriate water to beneficial use (Idaho Code § 14). Idaho adheres to the prior appropriation doctrine in that water rights are given to the first person to divert water and put it to a beneficial use. As water becomes less available, the most recent people to attain a water right are denied water first. Runoff, spring flow, and drain water are types of natural flow in Idaho.

Reservoirs must have a water right to store water in Idaho and are subject to prior appropriation. If there is a senior water user, downstream of a reservoir, requesting water and able to put it to a beneficial use, the reservoir must bypass the water instead of storing it. Federal reservoirs are authorized to store water for specific uses. The three reservoirs in the Boise System are primarily authorized for flood control and irrigation. The irrigation space is contracted out to individuals that can call upon water in the space when needed and is generally called stored water. Natural flow and stored water are collectively known as surface water.

Groundwater is another source of water and is pumped from aquifers. Groundwater users must also have a water right. Groundwater and surface water are administered conjunctively where in basins where groundwater and surface water are connected, which means that junior groundwater or surface water rights will be denied water if they negatively impact a senior groundwater or surface water user. So, if a groundwater pumper will reduce natural flow in a river that a senior user is entitled to, the groundwater pumper will be curtailed (not allowed to pump).

Irrigated Agriculture

Irrigated agriculture is a large part of the economy in the Boise River Basin; in 2012, crop sales totaled over $315 million in Ada and Canyon counties (USDA, 2016b). Surface water is distributed to farm land via an intricate system of canals and drains.

Over 54 crops types of crops and land use have been identified in the Boise River Basin between 2009 and 2015 in the crop land data layers (USDA, 2016a). Figure 7 shows the CDL in the western portion of the study area for 2015.

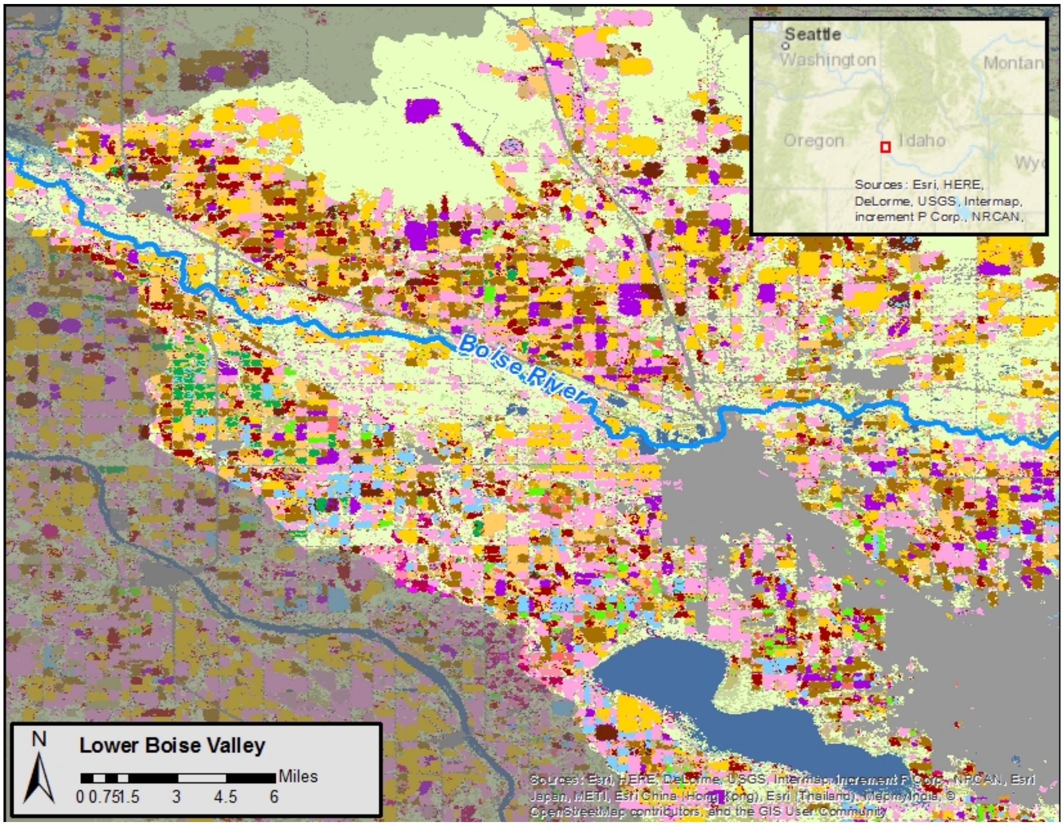


Figure 7: CDL of lower Boise Valley.

For this study, the 54 crop and land use types were aggregated into 12 categories (Table 1): beans, corn, developed, fallow, hay, herbs, non-agriculture, potatoes, sugar beets, trees, vegetables, and wheat. All of the lands were aggregated into one of the categories. Non-agriculture lands include water, range land, and forested lands. Hay includes all grass lands including pasture and lawns. Wheat includes all grains such as barley and oats.

Table 1: Crop CDL categories mapped to Crop categories used in this study.

CDL Category	Crop Category	CDL Category	Crop Category
Dry Beans	Beans	Onions	Veg
Corn	Corn	Peas	Veg
Developed/High Intensity	Developed	Peppers	Veg
Developed/Low Intensity	Developed	Pumpkins	Veg
Developed/Medium Intensity	Developed	Radishes	Veg
Developed/Open Space	Developed	Sweet Corn	Veg
Fallow/Idle Cropland	Fallow	Turnips	Veg
Alfalfa	Hay	Asparagus	Veg
Grass/Pasture	Hay	Cabbage	Veg
Other Hay/Non Alfalfa	Hay	Cauliflower	Veg
Herbs	Herbs	Cranberries	Veg
Mint	Herbs	Watermelons	Veg
Barren	Non-ag	Barley	Wheat
Deciduous Forest	Non-ag	Camelina	Wheat
Evergreen Forest	Non-ag	Clover/Wildflowers	Wheat
Herbaceous Wetlands	Non-ag	Dbl Crop WinWht/Corn	Wheat
Open Water	Non-ag	Hops	Wheat
Perennial Ice/Snow	Non-ag	Millet	Wheat
Shrubland	Non-ag	Oats	Wheat
Woody Wetlands	Non-ag	Other Crops	Wheat
Forest	Non-ag	Pop or Orn Corn	Wheat
Mixed Forest	Non-ag	Rye	Wheat
Water	Non-ag	Sod/Grass Seed	Wheat
Wetlands	Non-ag	Sorghum	Wheat
Potatoes	Potatoes	Spring Wheat	Wheat
Sugarbeets	Sugarbeets	Triticale	Wheat
Apples	Trees	Winter Wheat	Wheat
Cherries	Trees	Canola	Wheat
Grapes	Trees	Dbl Crop Barley/Corn	Wheat
Nectarines	Trees	Dbl Crop WinWht/Sorghum	Wheat
Peaches	Trees	Flaxseed	Wheat
Pears	Trees	Lentils	Wheat
Plums	Trees	Mustard	Wheat
Apricots	Trees	Other Small Grains	Wheat
Other Tree Crops	Trees	Rape Seed	Wheat
Prunes	Trees	Safflower	Wheat
Carrots	Veg	Soybeans	Wheat
Greens	Veg	Speltz	Wheat
Lettuce	Veg	Sunflower	Wheat
Misc Vegs & Fruits	Veg		

Figure 8 shows the crop totals for the aggregated categories used in this study not including developed and non-agriculture. Trees were not considered in this study because they have a very small acreage and they were assumed not to change from year to year. The hay category has by far the greatest number of acres in the study area.

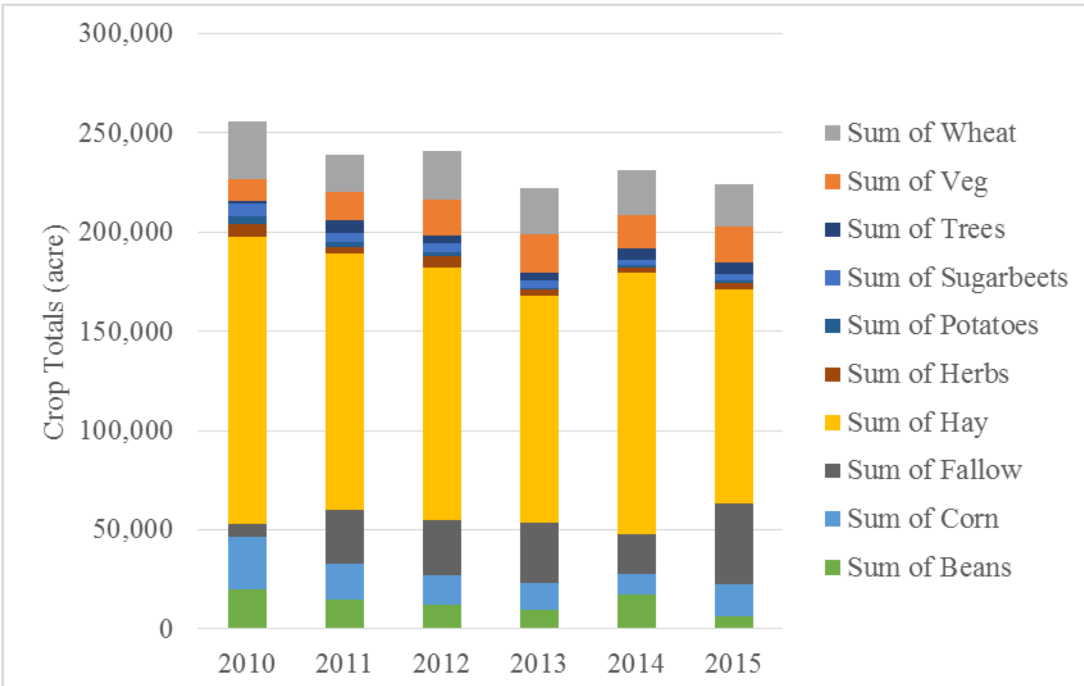


Figure 8: Crop totals as calculated from CDLs for study area.

Different crops types require differing amounts of water to maximize their yield in any given year. The evapotranspiration requirement for each crop is a key indicator of the amount of water that is needed for irrigation. Net irrigation requirement (NIR) can be calculated from evapotranspiration minus effective precipitation, and is the amount of irrigation required to grow a particular crop. The amount of evapotranspiration is plant and weather specific, so the choice of crop type and potential climate conditions are closely tied to the amount of irrigation water required.

Figure 9 shows the ranges of calculated NIR for eight of the crop categories in this study (trees are not considered and fallow land does not receive irrigation water) from 2000 through 2010. They were calculated using historical weather and the ET-Demands tool (Huntingtin, 2015), further described in Chapter 4. The box is the range of the NIR and the black line indicates the median NIR. From the plot, it can be seen that the total NIR varies by crop type. In addition, the sensitivity of NIR to weather conditions varies by crop in that some of the crops have a wider range of NIR for the same years and weather conditions. Hay has the largest need for water with the median value around 3 feet per acre, with herbs following at 2.5 feet per acre. Corn, Sugar Beets and Veg have a similar need for water as do Beans, Potatoes, and Wheat.

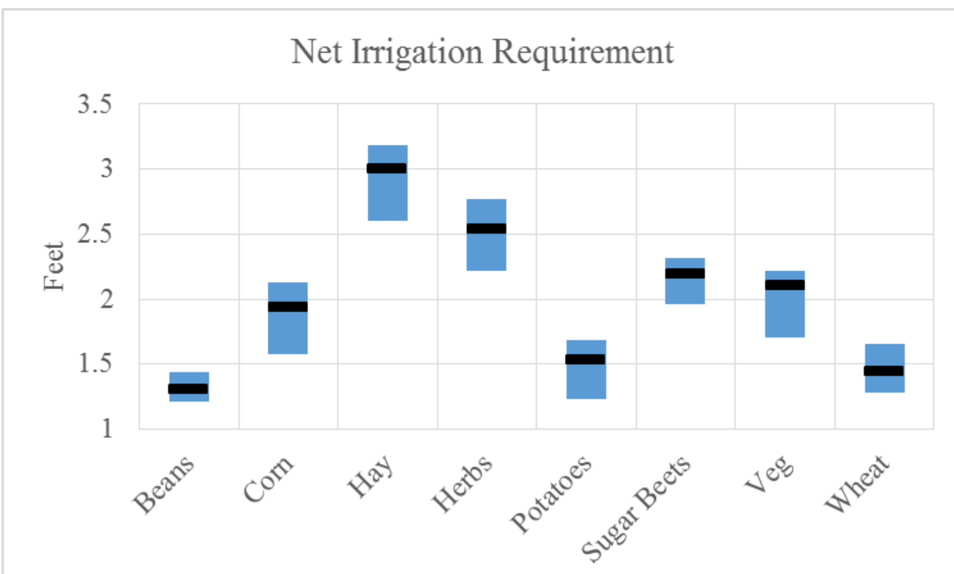


Figure 9: Historical range of net irrigation requirement for study crops; median represented by black line.

The NIR requirement for each crop type can be satisfied by water from varying sources. The sources available to specific lands are defined for districts, which represent lands that are served by a single canal or groups of canals. The designation of the lands associated with districts was defined using geospatial data from Idaho Department of Water Resources and diversions as defined in the RiverWare model of the Boise Valley (Reclamation, 2013b), further described in Chapter 4. Figure 10 shows the districts as defined for the study area.

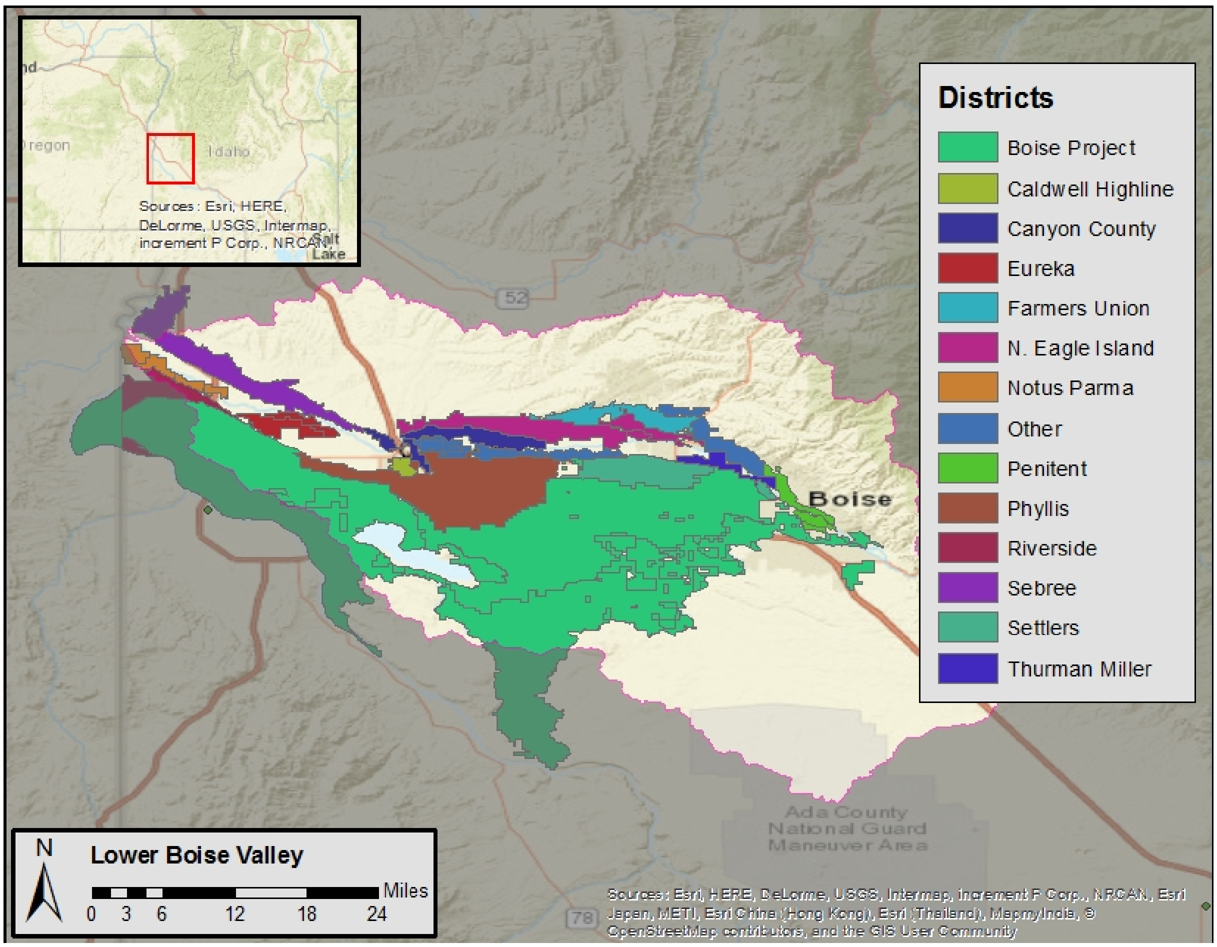


Figure 10: Districts in the study area.

Figure 11 shows the simulated amount of natural flow (not including drain water) and stored water delivered to the districts from 2010 through 2015. They were calculated using a RiverWare model of the Boise River system (Reclamation, 2013b), described further in Chapter 4. The Boise Project covers the most lands and also receives the most water in each year.

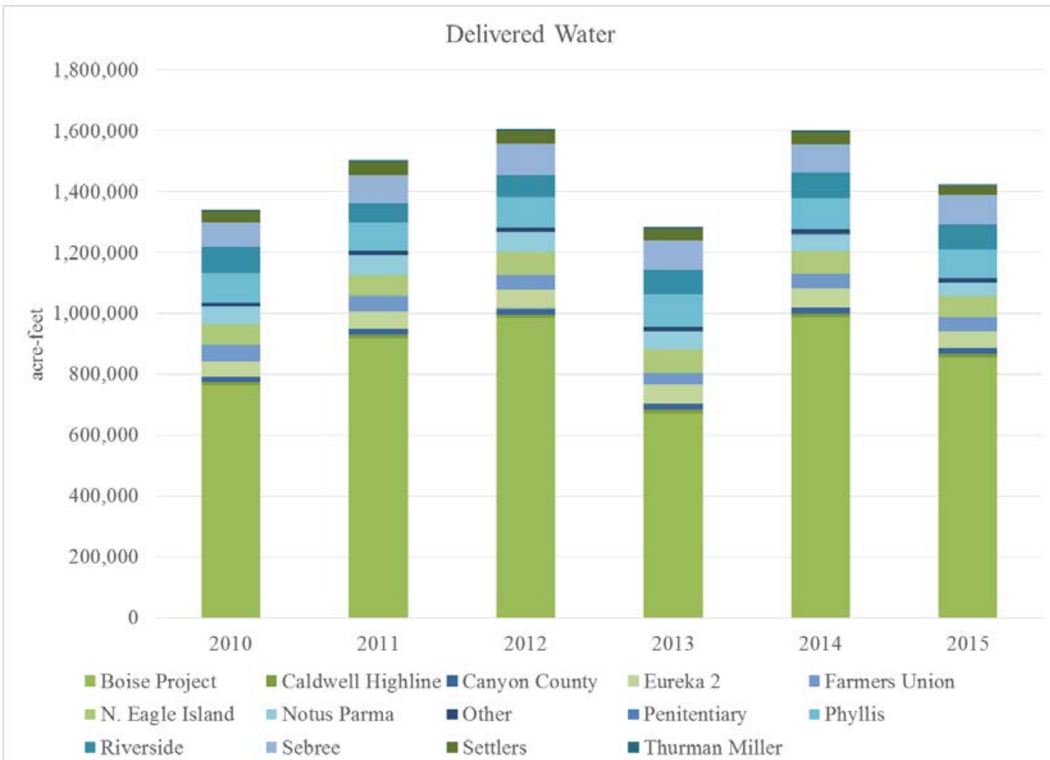


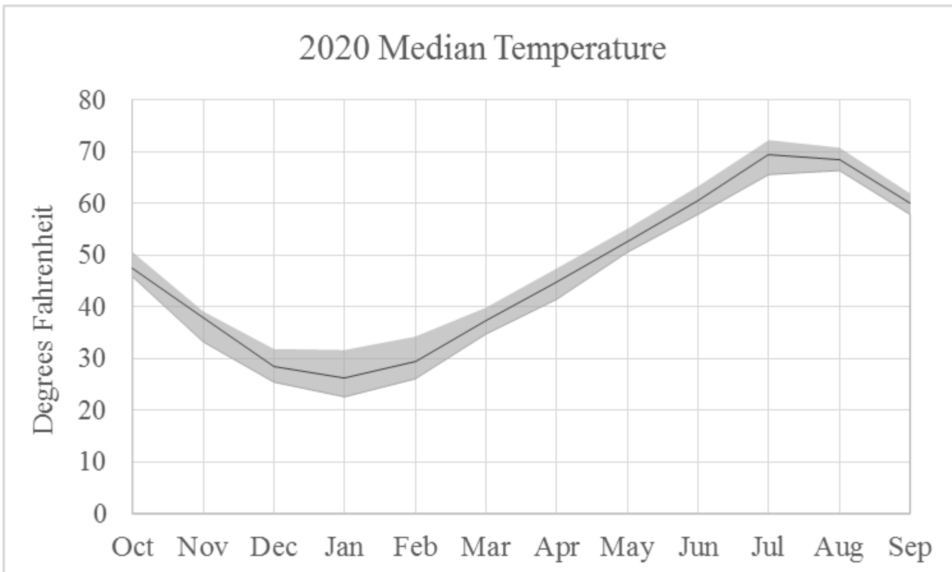
Figure 11: Simulated delivered water from the Boise River to the districts.

Future Climate

Future climate scenarios were selected from the Columbia River Basin Impacts Assessment study (CRBIA) (Reclamation, 2016b). CRBIA climate scenarios were defined using gridded temperature and precipitation output from Global Climate Models (GCM) developed through the fifth iteration of the Couple Model Intercomparison Project (CMIP5). The data is statistically downscaled to the 1/8th degree using the Bias Corrected and Spatially Downscaled (BSCD) method (Reclamation, 2013d).

The CRBIA scenarios represent trending conditions for future 30-year periods. They were developed using the Hybrid Delta Ensemble approach, which generally uses groups of GCM projections to develop change monthly factors that are then used to adjust historical temperature and precipitation. The 10-member groups were defined for future 30-year periods (2020s, 2040s, 2060s, and 2080s) to represent Less Warming/Dry, More Warming/Dry, Less Warming/Dry, More Warming/Wet conditions (Reclamation Hydro report). This study used scenario projections for the 2020s (2010-2039) and 2080s (2070-2099) median condition.

Figure 12 show the range (top) of temperatures and time series (bottom) for the Median 2020 scenario. The scenario indicates higher minimum winter temperatures than historical and lower summer high temperatures. The time series shows a gradual increase in minimum and maximum temperatures through time, but the increases are relatively small.



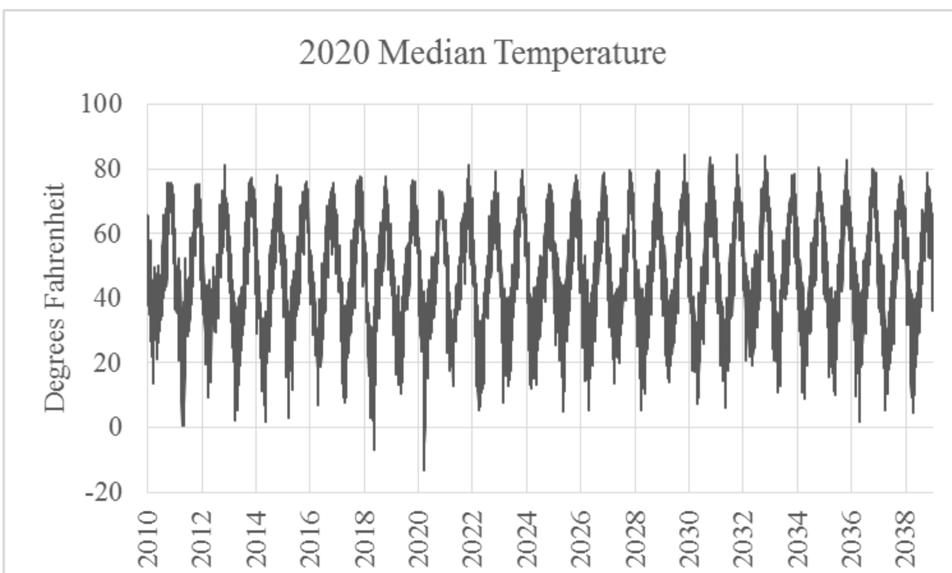


Figure 12: 2020 Median temperature range (top) and time series (bottom).

Figure 13 shows the range (top) and time series (bottom) of the 2080 Median scenario. The median temperatures are higher than the 2020 scenario and follow a similar trend.

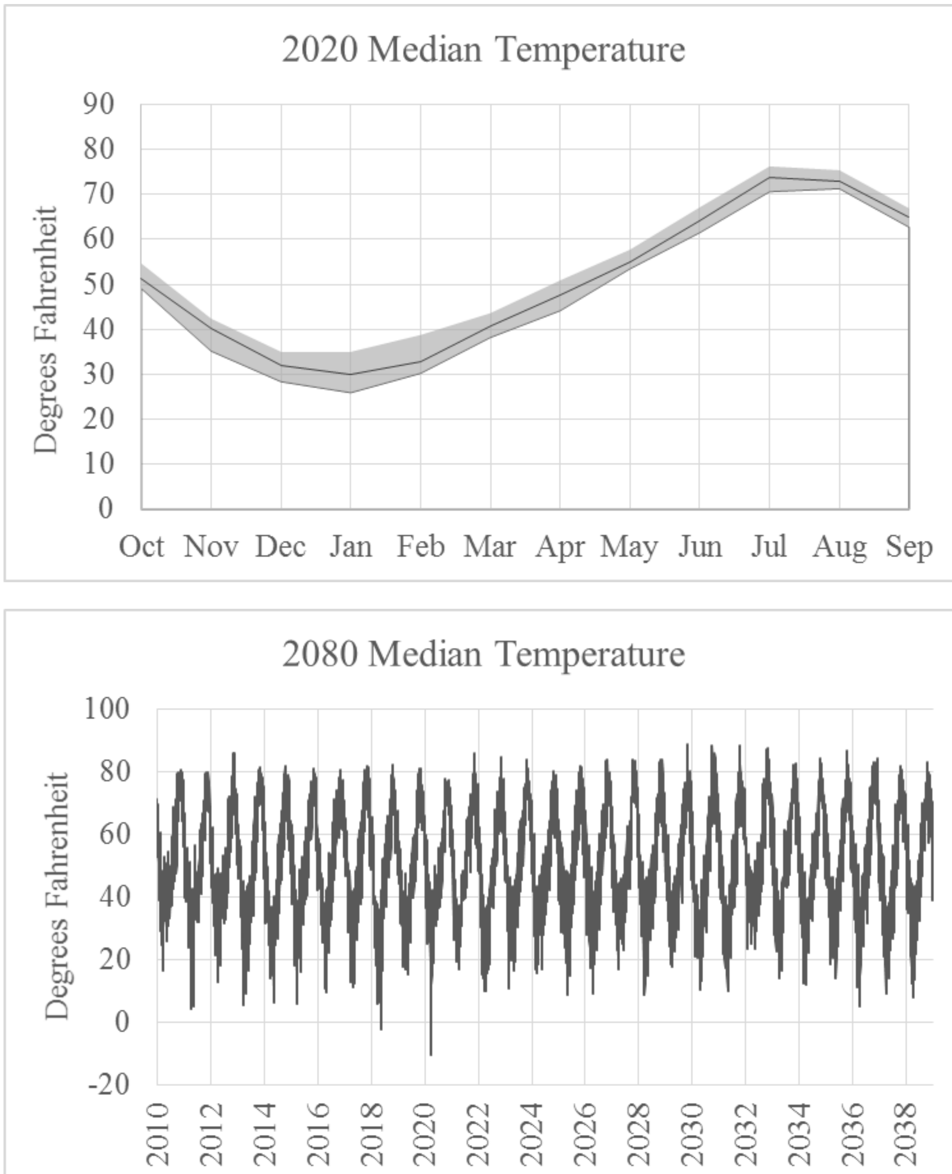


Figure 13: 2080 Median temperature range (top) and time series (bottom).

Figure 14 and Figure 15 show the range of monthly precipitation for the 2020 and 2080 median scenarios, respectively. Both scenarios show more precipitation in the winter and spring than historical.

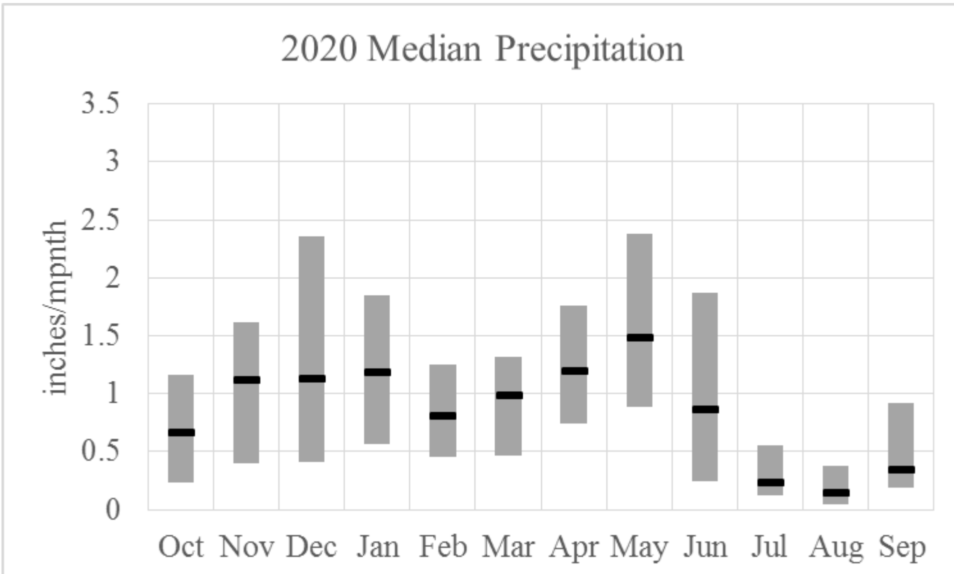


Figure 14: 2020 Median scenario precipitation totals for the Boise Valley as measured at the Boise Airport, median (black line) and 20 to 80 percent range (grey box).

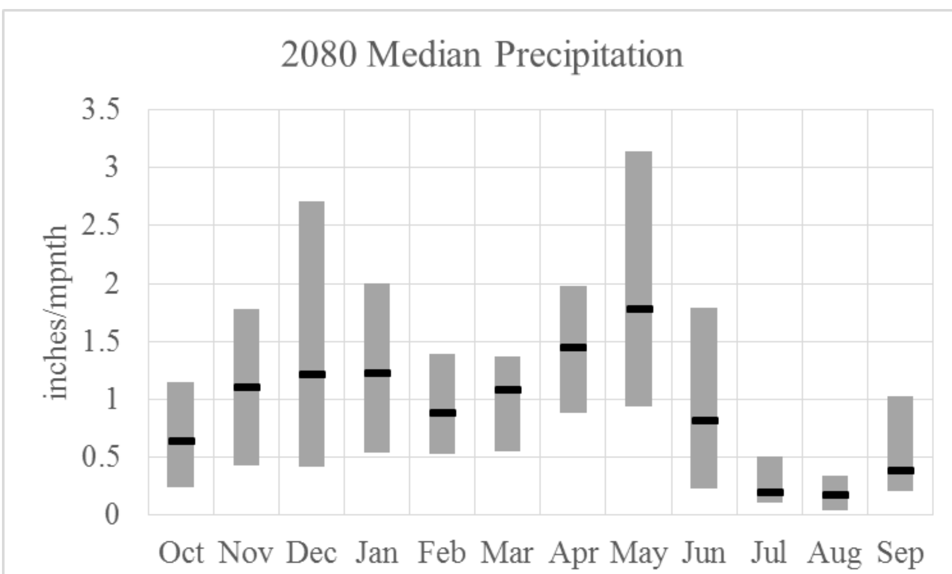


Figure 15: 2080 Median scenario precipitation totals for the Boise Valley as measured at the Boise Airport, median (black line) and 20 to 80 percent range (grey box).

The temperature and precipitation scenarios were used to develop future projected runoff using the Variable Infiltration Capacity (VIC) model (Liang et al., 1994) of the Columbia River Basin (Reclamation 2011a). The calculated runoff is used as input to the RiverWare model of the Boise Valley for the future projected climate scenarios. This method of using a hydrologic model such as VIC and a water management model such as RiverWare is widely used and is an accepted method for computing future climate adjusted water availability.

The temperature and precipitation scenarios were also used to develop net irrigation water requirement using the ET-Demands tool. The median 2020 scenario was used to represent current conditions for the testing period. Figure 16 shows the future projected reference annual ET for the 2020 and 2080 scenarios.

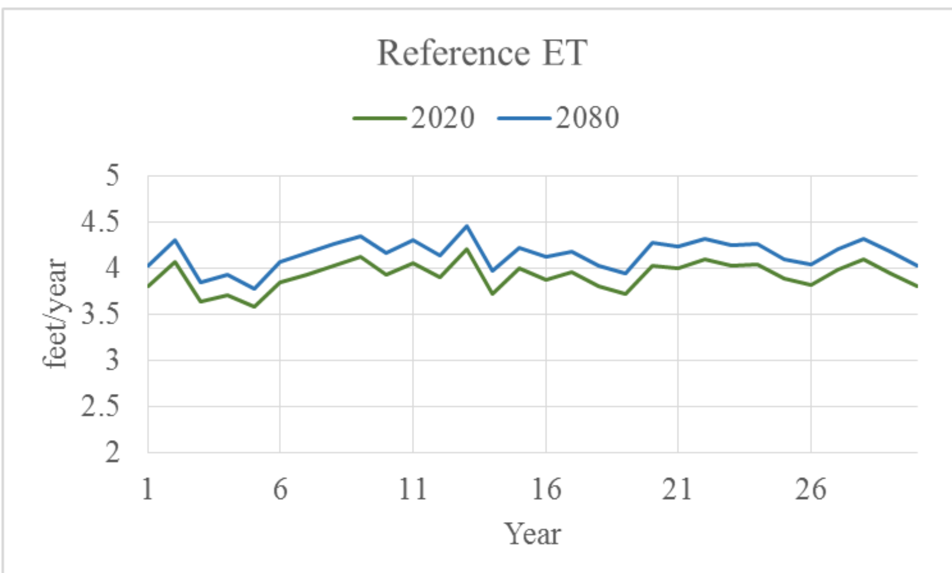


Figure 16: Future projected reference ET for 2020 and 2080 median scenarios.

Figure 17 shows the median future projected unregulated flow at the Glenwood Bridge for the selected future projected climate scenarios. As with many of the climate projections in the Pacific Northwest, the future projected flows in the Boise Basin are showing higher and earlier winter peaks as temperatures warm and less precipitation falls as snow. The 2020 projection is very similar to historical and will be used as the current conditions simulation for this study.

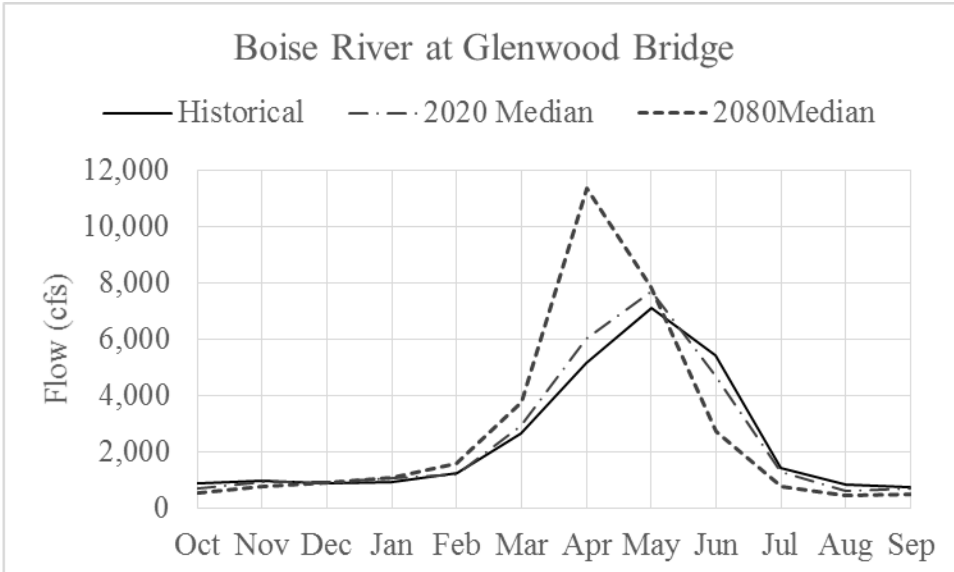


Figure 17: Future projected unregulated average monthly flows at the Boise River at Glenwood Bridge gage for the 2020 (dash dotted) and 2080 (dashed) future climate scenarios.

CHAPTER 3: APROACH - AGENT BASED MODEL[4]

Agent-based models (ABM) are a type of modeling tool that allows for the quantification of complex interactions between individuals or groups. Unlike standard equation based computational models, they can be programmed with the ability to adapt to influences from changing environments while allowing the individual agents to react to each other, and changes in the physical environment. In that sense, they are seen as tools that can more accurately reflect human decision making processes under a wide range of conditions. In addition, they allow for exploration of potential interactions that result from feedback loops and the identification of possible emergent patterns that result from these interactions (Heckbert et al., 2010; Matthews et al., 2007).

Attempts have been made to begin to understand how human decision making processes are impacted by changing environmental factors and vice versa. The fields of land use management and economics have benefitted from the use of ABMs, or Individual-Based Models (IBMs) as they are sometimes called, because both are better understood when decision making processes are included in the analysis, rather than simply focusing on physical or mathematical processes.

In an early application of an ABM for land use change, Rajan and Shibaski (2001) developed a model to explore the rural to urban land use conversion by linking biophysical crop yield, rural income, and urban land use all while being influenced by market, physical, and social factors. Parker et al. (2003) shows that ABMs are appropriate tools to explore land use changes because they more accurately represent complex spatial interactions under

[4] Portions of this section are excerpts from a preliminary investigation conducted by the author (Reclamation 2015) and are presented here for completeness.

heterogeneous conditions. In an applied example, Parker and Meretsky (2004) demonstrate the ability of an ABM platform to link landscape patterns to ecological and socioeconomic factors to explore the conversion of rural to urban lands.

Expansion on the land use conversion models has led to models that include more complex ideas of policy and ecosystem resilience. Over many years and iterations, Balmann et al. (1997, 2002), Berger (2001), and Happe (2004, et al. 2006) developed an ABM platform called AgriPoliS that is used to explore farm policy decisions in Europe (Kellerman et al. 2008). AgriPoliS has been successfully calibrated at the individual farm and aggregate levels and simulated reasonable results to farm policy changes. It incorporated a spatial environment, political environment, behavior of agents, markets, and land markets. However, none of the applications of AgriPoliS appeared to be related to water, likely because all of the applications were in areas that are not water limited. The relationships that link the physical, political, economic, and social changes together in this tool have the potential to become a reasonable foundation for the work in the proposed study, but will require additional work to incorporate the relationship to water.

The ability of an ABM approach to successfully incorporate water-focused relationships was demonstrated by Shluter and Pahl-Wostl (2007). This study used an ABM approach to explore system resilience in a semi-arid river basin that uses water for aquatic species (fish) and irrigated agriculture. Agents, representing farmers, made decisions on the number of fields to irrigate using their knowledge of water availability and past experience. They supplement their farming income with fishing, which impacts the aquatic ecosystem. Policy decisions were tested in the model to determine the resilience of the ecosystem and the model performed as expected.

Models in general are simplified representations of very complex systems. ABMs attempt to address the complexities in more advanced ways than any other type of modeling tool. Their ability to simulate individuals with unique decision making processes lend themselves to simulating systems where the decision making process is impacted by multiple factors that affect each individual differently. In addition, most ABMs can be developed using modular coding techniques where more features can be added as additional information becomes available. It is because of this that an ABM platform was selected for this study.

Of the over 80 ABM platforms available (Wikipedia, 2014), Repast Symphony (North et al., 2013) was selected for this study. Repast Symphony is based on the Java programming language, a commonly used programming language. It is open source, well documented, and relatively easy to learn and use.

Within the Repast Symphony platform, Java code is added by the user to define the agents, their behavior, and model output using Repast Symphony libraries for generic actions. The development of an ABM is described in the remainder of this chapter. The basic structure of the model and agents are described first. Next, development of the behavior criteria and input data are described. Last, a test case is presented.

Agents

The system developed for the model is designed to replicate a regulated river system with Crops, Farms, and Irrigation Districts acting as agents. The agents are related to each other in that a set of Crop agents belong to each Farm agent, and a set of Farm agents belong to each District (Figure 18). The agents to do not move in space in this version of an ABM; however space is used to contain the different agents.

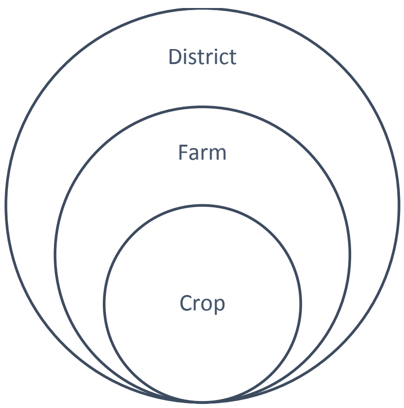


Figure 18: The relationship between District, Farm, and Crop Agents.

Crop Agent

The Crop Agent (Figure 19) type is assigned properties from a shapefile provided to the model: Crop Name, Crop Type, Farm Name, and Acres. Each Crop Agent is created and assigned to a Farm Agent using the Farm Name as an identifier.

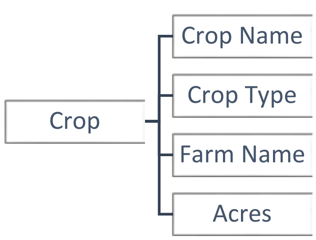


Figure 19: Crop Agent and its properties.

Farm Agent

The Farm Agent type represents the individual farmer and its unique decisions, and is the most important agent in the model. The Farm Agent is an abstract representation of a farmer and is defined by lands that are owned by a single individual or entity. The Farm Agent is defined using a shapefile that is provided to the model. The model reads the shapefile where it obtains predefined attributes that are used to create each farm and assign properties: Name, Available Crops, and Available Water, Probability Distributions, and District Name. The Available Crops are assigned using the crops that were grown historically by the Farm. Available Water is a ratio that represents the amount of irrigated acres by the farm in 2010 relative to all of the irrigated acres in the district. These five properties (Figure 20) are unique to each Farm Agent and are held constant through the model run period.

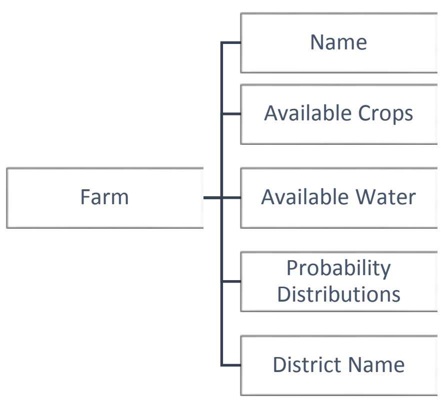


Figure 20: Farm Agent and its properties.

All of the Farm Agents begin each simulation with an assigned set of probability distributions that are the same for all of the Farms within a District. This set of probabilities is individualized for each Farm agent using its list of available crops prior to the first timestep, and then adjusted each timestep through the simulation period as the Farm Agent receives more information. The unique table of probabilities is retained by the Farm agent throughout the simulation period and is intended to reflect the unique behaviors and experiences of a single farmer.

District Agent

The District agent type represents an irrigation district or lands served by canals. Each Farm agent is assigned to a District. The District operates as a container for the Farms and is the manager of the water in the system. It has three properties, its name, efficiency, and available drain water (Figure 21). The efficiency property is single number that defines the efficiency of the canals and on-farm application within the District. The available drain water is also a single number that defines the total volume of drain water available to a District in any year.

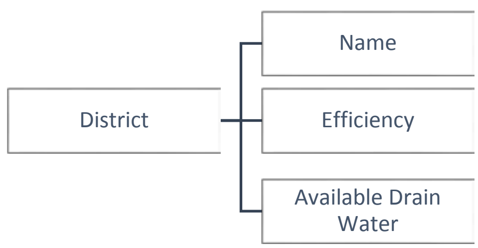


Figure 21: District Agent and its properties.

The Model

The agents interact during the model run time. The District Agents manage the water for the Farms, determining the amount of surface and drain water available to each Farm (groundwater is assumed to always be available). The Farm Agents manage their crops and use their historical and learned information to determine what to grow in subsequent years. The Crop Agent uses information about crop types to determine if it should change from one crop type to another. For example, the Crop Agent will not change type if it is developed land or non-agricultural land. It will also try to change crop types every year unless it is in the hay or herbs category.

At this time, the Farm Agents only communicate with their District or Crop Agents. An added feature at a later time might be to allow the Farms to communicate with each other.

Agent Behavior

The model runs on annual timesteps to represent a growing or irrigation season. An Initialization Step begins the model run. Decisions are made at two points during the year representing the beginning of the irrigation season and the end of the irrigation season. The first is that the Farm and Crop agents work together to determine the crops that should be grown for a given year, called the Crop Change step. The second occurs at the end of the irrigation season and determines if the farmer needs to update its perceptions of what should be grown given the outcome of the previous year, called the Update Probabilities step.

Initialization Step

During the Initialization Step, a Geographic Context (North et al., 2013) is set up to contain the agents. Generally a Context is a container for agents, and a Geographic Context allows the agents to exist in some relative space. This also allows for some of the model input data to be read from a shapefile, retaining its spatial information.

HashMaps are Java lists that are used to link a unique identifier to an Object, and are used in many places throughout the model. Agent objects are linked to their names using these lists.

One shapefile that contains the information about the Crop Agents and their associated Farms and Districts is read into the model. Table 2 shows the shapefile attributes that are assigned to agent properties.

Table 2: Relationship of shapefile attributes to agent properties for agents.

Agent Type	Shapefile Attribute	Agent Property
Farm	"Farm" + FarmID	Farm Name
	RWDistrict	District Name
Crop	FarmName + "Target_FID"	Crop Name
	c2009	Crop Type
	"Farm" + FarmID	Farm Name
	CropAcres	Acres
	Water	Available Water
District	RWDistrict	District Name
	Eff	Efficiency

The Available Crops properties are also read from the shapefile for each Crop Agent and are processed prior to being assigned to a Farm. For each Crop Agent, there is a column for each year with the crop type for that year. When read in, the crop types are transferred to an ArrayList (a list that is not dependent on size), duplicates are removed, and then it is assigned to the appropriate Farm agent.

Other information is read into the model from text files during the Initialization Step, including a time series of net irrigation requirement data for the particular scenario, a time series of available water for each district, and a table of probabilities for each district (discussed further in Chapter 4).

The table of empirical crop change probabilities is adjusted in this step for each Farm based on their available crops. Table 3 through Table 5 shows how one set of crop change probabilities would be adjusted for the crops available to an individual Farm. Table 3 shows the probabilities for one district in the Boise Valley, Pioneer. This table is interpreted by starting with the left most column and finding the current crop type, for example, Corn. A field growing Corn has a three percent change of growing Beans in the next year, a six percent chance of staying Corn, and so on. Note that Developed is constant for all of the current crop types except Developed; this based on the assumption that the conversion to developed land is not dependent on the type of crops that were formerly grown on the land.

Table 3: Empirical crop change probabilities for Pioneer Irrigation District.

	Beans	Corn	Developed	Fallow	Hay	Herbs	Non Ag	Potatoes	Sugar beets	Trees	Veg	Wheat	Sum
Beans	0.10	0.02	0.09	0.01	0.29	0.01	0.00	0.00	0.09	0.00	0.03	0.35	1.00
Corn	0.03	0.06	0.09	0.01	0.23	0.06	0.00	0.00	0.03	0.00	0.13	0.35	1.00
Developed	0.00	0.00	0.66	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Fallow	0.11	0.03	0.09	0.06	0.56	0.00	0.03	0.00	0.00	0.00	0.06	0.05	1.00
Hay	0.08	0.05	0.09	0.02	0.34	0.05	0.01	0.01	0.05	0.00	0.07	0.23	1.00
Herbs	0.10	0.05	0.09	0.01	0.39	0.02	0.00	0.01	0.01	0.00	0.06	0.26	1.00
Non Ag	0.02	0.03	0.09	0.09	0.54	0.00	0.14	0.02	0.00	0.00	0.01	0.04	1.00
Potatoes	0.10	0.05	0.09	0.00	0.16	0.13	0.00	0.00	0.04	0.00	0.23	0.19	1.00
Sugar beets	0.09	0.17	0.09	0.00	0.16	0.02	0.01	0.00	0.22	0.00	0.03	0.22	1.00
Trees	0.49	0.01	0.09	0.01	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Veg	0.19	0.06	0.09	0.01	0.23	0.00	0.00	0.00	0.07	0.00	0.10	0.25	1.00
Wheat	0.12	0.08	0.09	0.01	0.40	0.01	0.01	0.00	0.10	0.00	0.07	0.11	1.00

Table 4 shows the available crops for one Farm within the Pioneer District. The ones indicate that the crop type had been grown on land owned by this farmer in the six years that data is available. A zero indicates that the crop type has not been grown by this farm. Non Ag is always set to zero because it was assumed that no irrigated lands would convert back to forested or other non-developed lands. Developed and Fallow are always one because it was assumed that any field could be developed or fallowed in any year.

Table 4: Available crops for one Farm in the Pioneer District.

	Beans	Corn	Developed	Fallow	Hay	Herbs	Non Ag	Potatoes	Sugar Beets	Trees	Veg	Wheat
Avail Crops	1	1	1	1	1	1	0	0	1	1	1	1

Table 5 shows the adjusted probabilities for this Farm based on its available crops. Note that all of the probabilities of crops with zeros in Table 4 are zeroed out. Next, it is assumed that the Developed probability will remain the same in the first timestep, so the remaining probabilities are normalized so that all, including Developed, add to one.

Table 5: Adjusted probabilities for Farm in Pioneer District based on available crops.

	Beans	Corn	Developed	Fallow	Hay	Herbs	Non Ag	Potatoes	Sugarbeets	Trees	Veg	Wheat	Sum
Beans	0.10	0.02	0.09	0.01	0.29	0.01	0.00	0.00	0.09	0.00	0.03	0.35	1.00
Corn	0.03	0.06	0.09	0.01	0.23	0.06	0.00	0.00	0.03	0.00	0.13	0.35	1.00
Developed	0.00	0.00	0.66	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Fallow	0.11	0.03	0.09	0.06	0.56	0.00	0.00	0.00	0.00	0.00	0.06	0.05	1.00
Hay	0.08	0.05	0.09	0.02	0.34	0.05	0.00	0.00	0.05	0.00	0.07	0.23	1.00
Herbs	0.10	0.05	0.09	0.01	0.39	0.02	0.00	0.00	0.01	0.00	0.06	0.26	1.00
Non Ag	0.02	0.03	0.09	0.09	0.54	0.00	0.00	0.00	0.00	0.00	0.01	0.04	1.00
Potatoes	0.10	0.05	0.09	0.00	0.16	0.13	0.00	0.00	0.04	0.00	0.23	0.19	1.00
Sugar beets	0.09	0.17	0.09	0.00	0.16	0.02	0.00	0.00	0.22	0.00	0.03	0.22	1.00
Trees	0.49	0.01	0.09	0.01	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Veg	0.19	0.06	0.09	0.01	0.23	0.00	0.00	0.00	0.07	0.00	0.10	0.25	1.00
Wheat	0.12	0.08	0.09	0.01	0.40	0.01	0.00	0.00	0.10	0.00	0.07	0.11	1.00

Crop Change Step

The model loops through each Farm Agent during the Crop Change step to determine the crops to be grown for the upcoming irrigation season. Each Farm Agent loops through its Crop Agent list to determine the type of crop that should be grown. The Crop Agent makes its determination about what to grow using the set of probabilities of changing from one crop to another. The probabilities are converted to a lookup table (in the form of a HashMap) that list the probabilities in the identifier column and the Crop Type in the data column. An identifier is selected from the lookup using a random number generator, and the crop type associated with the identifier is assigned to the agent's Crop Type.

As a simple example is presented here for illustration purposes. There is a 20 percent probability that a crop will change from corn to potatoes, 20 percent probability it will change from corn to vegetables, and 60 percent probability it will change from corn to wheat. Table 6 is the lookup table that would be developed for 10 items. Using a random number generator, a number from 0 to 9 is selected and the corresponding crop type is assigned to the agent's Crop Type.

Table 6: Example of lookup table for crop selection.

Identifier	Crop Type
0	Potatoes
1	Potatoes
2	Veg
3	Veg
4	Wheat
5	Wheat
6	Wheat
7	Wheat
8	Wheat
9	Wheat

The Crop Agent has 12 possible crop types it can change to, so instead of 10, the lookup table generates for integers from 0 to 9,999.

This selection has additional constrains to better represents crop choices that result from crop rotation. Lands that are in the Non Ag, Trees, and Developed categories do not change once assigned to that Crop Type. The remaining lands with Crop Types that are not Hay or Herbs must change every year.

Lands in the Hay and Herbs crop categories do not rotate every year and may be planted for multiple years. These lands are allowed to remain the same crop type from year to year, but they may change in any year. Hay remains the same in 90 percent of the years and Herbs remain the same in 75 percent of the years. A probability lookup table and random number generator is used to determine if each crop type will change.

Update Probabilities Step

The Update Probabilities step occurs at the end of the irrigation season and is meant to simulate the reaction of the farmer to the previous growing season. A quasi-Bayesian updating technique was developed through trial and error to simulate the farmer's reactions to varying conditions. Bayesian updating is the theory that a probability will change as new information is learned. In this case, it is applied to the empirical crop change probabilities table for each individual farm in each timestep. However, the traditional version of Bayesian updating is not used, hence the term quasi-Bayesian, since the farmer's decisions were determined to be random in any given year.

Available data for the Boise Valley was used to conduct an investigation into the possible correlation between historical acres planted, yield, price, growing degree day, and volume of water available. Acres planted, yield, and the commodity price information was available for Ada and Canyon counties through the National Agricultural Statistics Service (USDA, 2016b). These data were only available for a subset of the crops grown in the Boise Valley (dry beans, feed corn, alfalfa hay, potatoes, sugar beets, and spring wheat), so only these crops were analyzed. Data were consistently available by county from 1988 through 2006. Between 2007 and 2014, if county level data were not available, a linear regression was developed for the available county data to the available statewide data for Idaho to fill in the gaps.

Growing degree day (GDD) is a measure of the amount of heat units that are needed for a crop to complete its growing cycle, and it can be used to estimate planting and harvest dates. It can be calculated in a variety of different ways, and for this analysis, GDD was calculated using the equations given in Allen and Robinson (2009).

The volume of water available was calculated using the historical volume of water that flowed into the system upstream of Lucky Peak reservoir for the entire water year (Reclamation, 2016a). This is a representative volume of the amount of water available for irrigation in a given year.

The information for each crop was read into the statistical program, R (R, 2015), to evaluate possible correlations. In particular, the data were plotted against each other to determine if there were any apparent correlations by inspection. In these plots, if the values were correlated, one would expect to see the points lining up in a straight line. Figure 22 for corn is representative of all of the crop types that were evaluated, and it can be seen from this plot that little if any correlation exists between these parameters.

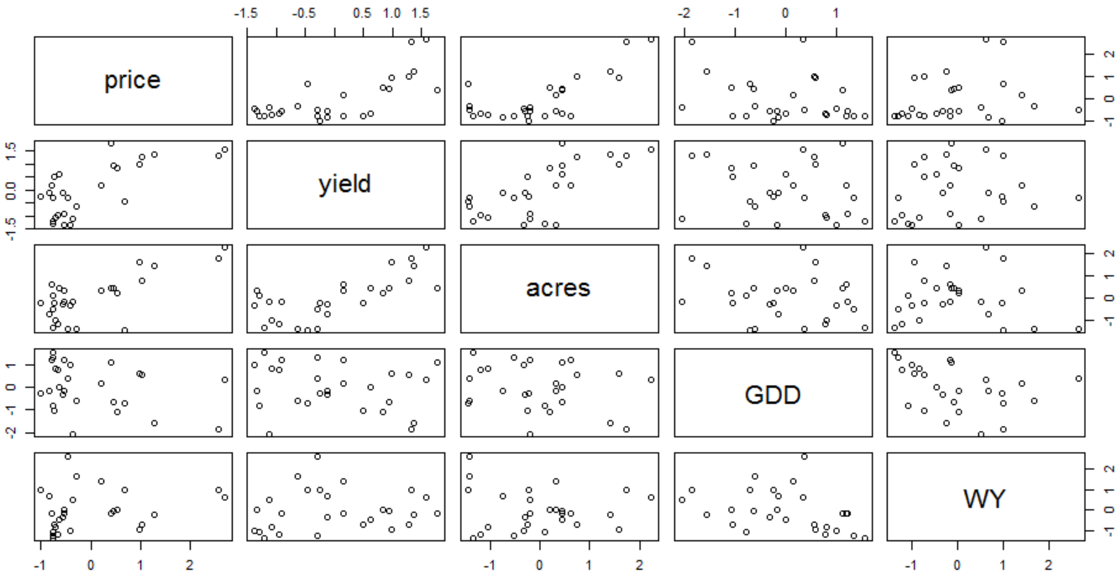


Figure 22: Plot of standardized parameters for corn.

To further investigate, an attempt was made to fit a linear model of each parameter to the quantity of acres grown for each crop type. The p value for each linear model exceeded 0.05 and therefore showed that a linear model could not be fit to the data. This unexpected result led to the development of a non-traditional approach that could incorporate the recent experiences of the farmer into the Farm crop change probability table.

Although there were no relationships annually, some of the parameters correlated (namely yield, price, and acres planted) using a simple five-year moving average. Table 7 summarizes the resulting equations and p-values from this analysis. PA is the acres planted in year y, Y is the five-year moving average of the yield in the previous five years, and P is the five-year moving average of the yield in the previous five years. For Hay, harvested acres is reported instead of acres planted, so HA (harvested acres) is used in the equation. Only the significant parameters were included in the equations, so some of the equations are only based on yield. All of the equations were calculated using standardized values and then were converted back to actual values.

Table 7: Table of equations used in agent based model to estimate acres planted in each year.

Crop Type	Equation	p-value
Beans	$PA = -30 * Y + 75744$	4.535E-04
Corn	$PA = 329 * Y - 12637$	2.044E-07
Hay	$HA = -30172 * Y + 223462$	2.549E-03
Potatoes	$PA = -28 * Y + 21389$	7.010E-05
Sugar beets	$PA = -2279 * Y + 1165 * P + 58957$	1.560E-03
Wheat	$PA = -1463 * Y + 291263$	2.142E-10

These relationships led to idea that 5-year moving average of yields were a driving component to the choices that a farmer might make from year to year. Yield can be a surrogate for available water since yields will decrease if the crop does not receive its optimal amount of water. The Boise Valley is unique in the Western US because in most years, there is enough water to meet irrigation needs, either from surface or groundwater water. So, instead of using yield as a limiting factor that might cause a farmer to choose one crop over another, a relationship was developed for the potential price received to the cost of production. Water cost changes based on the source, so as water availability changes, the farmer may adjust behavior based on potential profit.

Equation 1 is the updating equation that was developed using the ideas described above:

Equation 1: $$f_c = \frac{p_c * a}{(w + cv_c) * a + cf_c} + s_c$$

where f is the updating factor, c is the crop type, p is the price received (dollars per acre), a is the size of the field (acres), w is the cost of water (dollars per acre), cv is the variable production cost of the crop (dollars per acre), cf is the fixed cost (dollars per farm), and s is an adjustment factor for hay and corn (unitless). The factors are limited to minimum and maximum values (called factor limits) to ensure changes do not occur too rapidly or slowly.

These minimum and maximum values are adjusted to calibrate the model to available measured data.

The crop change probability table is adjusted during the Update Probabilities step for each Farm and each crop type that the Farm is growing in the current year. The probability of any crop changing to the current crop is updated by multiplying by the factor, f_c, represented by a column of the crop change probability table. After each update of the probabilities for a crop, the row is normalized back to one.

The crop change probabilities in Table 5 for a Farm in the Pioneer District are used here to illustrate an example of the method used to update the table for corn. The factor is calculated to be 0.8 (Table 8). Multiplying the ratio by all of the values in the corn column reduces the total in all of the rows, so the next step is to normalize the table using the same method conducted in the Initialization Step.

Table 8: Crop change probabilities with updated, but not normalized, corn values.

	Beans	Corn	Developed	Fallow	Hay	Herbs	Non Ag	Potatoes	Sugar beets	Trees	Veg	Wheat	Sum
Beans	0.10	0.02	0.09	0.01	0.29	0.01	0.00	0.00	0.10	0.00	0.04	0.35	1.00
Corn	0.03	0.05	0.09	0.01	0.23	0.06	0.00	0.00	0.03	0.00	0.13	0.35	0.99
Developed	0.00	0.00	0.66	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Fallow	0.11	0.02	0.09	0.06	0.58	0.00	0.00	0.00	0.00	0.00	0.06	0.05	0.99
Hay	0.08	0.04	0.09	0.02	0.35	0.05	0.00	0.00	0.05	0.00	0.07	0.23	0.99
Herbs	0.10	0.04	0.09	0.01	0.39	0.02	0.00	0.00	0.01	0.00	0.06	0.26	0.99
Non Ag	0.02	0.03	0.09	0.11	0.66	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.99
Potatoes	0.10	0.04	0.09	0.00	0.16	0.13	0.00	0.00	0.04	0.00	0.23	0.20	0.99
Sugar beets	0.09	0.14	0.09	0.00	0.16	0.02	0.00	0.00	0.22	0.00	0.03	0.22	0.96
Trees	0.49	0.01	0.09	0.01	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Veg	0.19	0.05	0.09	0.01	0.23	0.00	0.00	0.00	0.07	0.00	0.10	0.25	0.99
Wheat	0.12	0.06	0.09	0.01	0.40	0.01	0.00	0.00	0.10	0.00	0.07	0.12	0.98

Note that when the values are normalized, the probabilities of the crops that are not corn increase (Table 9). So, corn is less likely to be chosen in the next year, but the remaining crops are more likely to be chosen. As in the initialization step, the value for developed land is the same for all crops, but the value changes in each timestep using data that is input into the model (in this example, the developed probabilities remained the same as the previous timestep).

Table 9: Updated crop change probabilities table.

	Beans	Corn	Developed	Fallow	Hay	Herbs	Non Ag	Potatoes	Sugar beets	Trees	Veg	Wheat	Sum
Beans	0.10	0.02	0.09	0.01	0.29	0.01	0.00	0.00	0.10	0.00	0.04	0.35	1.00
Corn	0.03	0.05	0.09	0.01	0.24	0.06	0.00	0.00	0.03	0.00	0.13	0.36	1.00
Developed	0.00	0.00	0.66	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Fallow	0.12	0.02	0.09	0.07	0.59	0.00	0.00	0.00	0.00	0.00	0.06	0.05	1.00
Hay	0.08	0.04	0.09	0.02	0.36	0.05	0.00	0.00	0.05	0.00	0.07	0.24	1.00
Herbs	0.10	0.04	0.09	0.01	0.40	0.02	0.00	0.00	0.01	0.00	0.06	0.26	1.00
Non Ag	0.02	0.03	0.09	0.11	0.67	0.00	0.00	0.00	0.00	0.00	0.02	0.05	1.00
Potatoes	0.10	0.04	0.09	0.00	0.17	0.14	0.00	0.00	0.04	0.00	0.23	0.20	1.00
Sugar beets	0.09	0.15	0.09	0.00	0.16	0.02	0.00	0.00	0.23	0.00	0.03	0.23	1.00
Trees	0.49	0.01	0.09	0.01	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
Veg	0.19	0.05	0.09	0.01	0.24	0.00	0.00	0.00	0.07	0.00	0.10	0.26	1.00
Wheat	0.13	0.07	0.09	0.01	0.41	0.01	0.00	0.00	0.10	0.00	0.07	0.12	1.00

Cost of Water Calculation

The amount of water needed by each Farm in each timestep is calculated using the net irrigation required (NIR) and the acreages of crops that grown by that Farm. NIR is the amount of water needed for crop growth and is dependent on the crop type, weather conditions, and soil type. NIR is calculated external to the model using the ET-Demands tool and estimated weather data specific to the scenario being evaluated. The amount of surface water (not including drain water) available to the Farm (sw) is calculated using the amount of surface water (not including drain water) available to the Farm's District (dsw) adjusted by the system efficiency (e) and the Farm's available water fraction (wf) (Equation 2).

Equation 2: $$sw = wf * dsw * e$$

Recall the Farm's available water fraction is the amount of acres irrigated by the Farm in 2010 relative to the total number of irrigated acres within the district. Some of the districts with lower elevation lands closer to the river have access to drain water. The amount of drain water available to an individual Farm is calculated using the amount of drain water available to the Farm's District (ddw) and the Farm's available water fraction (wf) (Equation 3).

Equation 3: $$dw = wf * ddw$$

Delivery of surface water (not including drain water) within a district is the least expensive source of water, so it used first. If the amount of water surface available to the Farm exceeds the NIR, the cost of surface water is multiplied by the NIR to determine the cost of water for the Farm (Equation 4).

Equation 4: $$p = sc * NIR$$

If the amount of surface and drain water exceed the NIR, the amount of surface water available is multiplied by the cost of surface water and the difference between the surface water available and NIR is multiplied by the cost of drain water (Equation 5)

Equation 5: $$p = sc * sw + dc * (NIR - sw)$$

If the amount of surface water and drain water available is less than NIR, the amount of surface water available is multiplied by the cost of surface water, the difference between the surface water available and NIR is multiplied by the cost of drain water, and the difference between NIR and available surface an drain water is multiplied by the cost of groundwater (Equation 6).

Equation 6: $$p = sc * sw + dc * (NIR - sw) + gc * (NIR - sw - dw)$$

This follows the assumption that if there is not enough surface and drain water during the irrigation season, the Farmer and/or District would supplement with groundwater.

CHAPTER 4: METHODS - DATA PREPARATION for the AGENT BASED MODEL

The agent based model requires geospatial and tabular data as input. This data requires processing before it can be used in the model. This section describes the data preparation necessary for the model.

District-Farm-Crop Shapefile

The primary spatial dataset that is required by the model is the District-Farm-Crop Shapefile. For this work, it was developed using actual data from the Boise Valley. “Farms” were identified first using county parcel data for Ada and Canyon counties. Farms were defined as any parcel of land that was owned by a single party that was at least five acres (Figure 23).

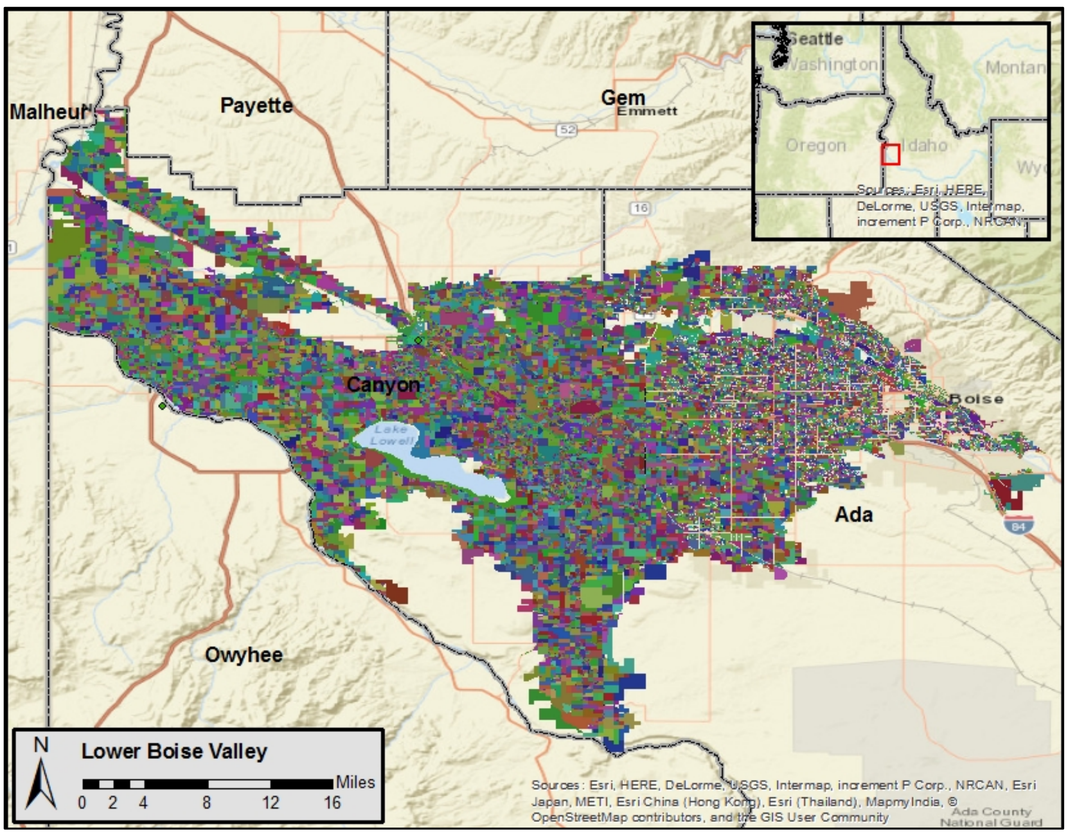


Figure 23: Map of defined Farms for Ada and Canyon counties. Colors indicate separate Farms.

The Farms were spatially joined to larger polygons that defined Irrigation Districts in the Boise Valley (Figure 10). Developed land and subdivisions that are within district boundaries were included in this Farm designation to completely cover the area of interest, but were dissolved into larger polygons that covered as much of the developed land as possible.

Next, Cropland Data Layers (CDLs) were obtained from the US Department of Agriculture CropScape online database for the years 2009 through 2015 (USDA, 2016). CDLs are pixel-based spatial datasets that indicate the types of crops grown in a particular year. The 2009 CDL was converted into polygon shapefiles by dissolving the pixels into polygons with similar crop types. These polygons defined a static set of fields that were then spatially joined to the farms. For simplicity, it was assumed that the fields would remain linked to the same Farm and would remain the same size throughout any simulation timeframe. However, the type of crop grown on the field could change, and the field could change from irrigated lands to developed lands.

The CDLs in the Boise Valley show that there are 54 different crop categories defined in the Valley. These were grouped into twelve crop categories (labeled Crop Types in the Agent) and are shown in Table 1.

The types of crops that each Farm has grown historically were determined by observing the crop categories that were contained in the fields of a particular Farm from 2009 through 2015. Most of the crops grown in the Boise Valley have a rotation that is six years or less, so it is reasonable to assume that the range of the crops grown by a particular Farm would be seen in this seven year window. It was assumed that Farm investments into equipment, knowledge, and experience would limit the crop choice for subsequent years, so this historical look at crop types grown by each farm is an important input to the agent based model.

It was not possible to determine the amount of water that was delivered to individual Farms within a district from available data. In lieu of this information, an estimate of the amount of water needed by each field was calculated using the size of the field and Equation 7.

Equation 7 $$wf_f = \frac{\sum_f fa}{\sum_d fa}$$

The field sizes, f, were summed for the fields in each Farm, f, and divided by the sum of the fields in the district, d, to determine a within district fraction of water delivered to each Farm, called Available Water Fraction, wf.

Crop Change Probabilities Table

The Crop Change Probabilities Table was calculated using the data developed for the District-Farm-Crop Shapefile. Specifically, empirical probability distributions were calculated by counting the number of acres of crops that changed from one crop type to another in a given year. For example, the number of acres that were corn in 2010 that changed to wheat in 2011 were counted. This was done for each irrigation district using the assumption that each district may behave differently given their water rights and management practices. The number of acres were then normalized so that the values added to one for the prior year's crop type, with a constant value for change to Developed land.

Crop Demand Timeseries

Timeseries of net irrigation water requirement (NIR) were developed using ET-Demands model developed through a partnership with the Bureau of Reclamation and Dessert Research Institute for evaluation of future demands in the West-Wide Climate Risk Assessment (Huntington, 2015). ET-Demands calculates crop ET (ET_C) using reference ET (ET_0) and a crop coefficient (K_c). NIR is ETc minus effective precipitation, or precipitation that resides in the root zone.

Inputs for the ET-Demands tool include site specific weather and soil data, estimates of ET_0, and crop specific parameters. Soil data and calibrated crop specific parameters were developed and calibrated for the ID1380 site in the lower Boise Valley during the WWCRA study (Huntington, 2015); those values were used in the calculations for this study. Historical and future weather data developed for the Columbia River Basin Impacts Assessment were used in this study (Reclamation, 2016b).

Estimates of ET_0 were developed using the Ref-ET tool from the University of Idaho (Allen 2013). The Ref-ET tool uses the historical or future projected daily minimum and maximum temperature, precipitation, and wind speed to calculate reference ET values using the standardized ASCE-PM method (ASCE-EWRI, 2005) (historical wind speed is used for both historical and future projected climate simulations). The ASCE-PM method also requires inputs of solar radiation and air humidity; these are calculated using the temperature inputs within the Ref-ET tool.

NIR is calculated in the ET-Demands tool using the calculated ETc and a water balance model to determine the effective precipitation in the root zone. NIR is the amount of additional water, not provided by rain, needed for a crop to reach maximum yields. Output from the ET-Demands tool is read directly into the agent based model for each representative crop type. The calculated annual NIR is used in the equation to calculate the cost of water.

Water Delivery Timeseries

Water delivery is calculated for each district using a RiverWare (Zagona et al., 2001) model of the Boise Valley (Reclamation, 2013b). RiverWare is a model that is designed to simulated regulated river-reservoir systems. This particular model distributes water throughout the Boise Valley using rules that confine the distribution to the physical and legal limitations in the system.

Inputs to the Boise Valley RiverWare model include unregulated inflows to each of the six reaches in the system, an estimate of irrigation diversions at each of the water user objects representing districts, natural flow and storage rights, and reservoir operating criteria. When simulating future projected climate conditions, the unregulated flows are adjusted using future projected streamflow estimates that were developed using the VIC (Liang et al., 1994) model for the Columbia River Basin Impacts Assessment (Reclamation, 2016b).

The model provided estimates of water deliveries to each district, separating out the natural flow and stored water components. The values computed by the RiverWare model are the total diversion of water from the river at a particular location. This is different than the NIR. The total diversion includes NIR plus system conveyance losses that include evaporation during transportation and seepage from canals. It also includes losses that occur on-farm that may include seepage and evaporation. The total water delivery estimates are read into the agent based model. When using these values in the model, they are multiplied by an estimate of system efficiency that was calculated for the Hydro-Economic Model study and is a property of each district (Schmidt et al., 2013).

CHAPTER 5: RESULTS - TESTING the AGENT BASED MODEL

The intent of the agent based model is to compute future agricultural water needs in a regulated river system. In order to test the model, output files are written containing summarized computations from the model during runtime including the amount of water required to irrigate the crops in each district and the total number of crop acres in each district. Historical crop totals for individual districts were only available for seven years, 2009 through 2015, when CDLs were available.

Constant crop price received, farm cost of operation, and cost of water for each type were input into the model. Table 10 shows the price received per acre of each crop type and the farm cost of operation without water (AgBiz, 2016). The profit potential assumes 10 acres and does not consider the cost of water. The crops with the highest profit potential are Potatoes and Vegetables.

Table 10: Price received and cost of operation for each crop used in model testing.

Crop	**Price Received ($/acre)**	**Fixed Cost ($/Farm)**	**Variable Cost ($/acre)**	**Profit Potential ($/Farm[5])**
Beans	$912.00	$334.02	$445.63	$4,329.68
Corn	$1408.00	$385.88	$896.61	$4,728.02
Hay	$1,312.50	$398.71	$585.31	$6,873.19
Herbs	$2,090.00	$727.08	$1,204.78	$8,125.12
Potatoes	$3,975.00	$1,021.43	$2,429.54	$14,433.17
Sugar Beets	$1,620.00	$565.30	$1,164.52	$3,989.50
Vegetables	$4,537.50	$826.71	$2,859.90	$15,949.29
Wheat	$742.50	$302.01	$404.94	$3,073.59

[5] Revised from Final submitted version which had the units as $/acre.

The cost of each water type was taken from a hydro-economic study conducted in the Boise Valley in 2014 (Schmidt et al 2014). In this study, the cost of surface water (not including drain water) was estimated to be an average of $5.89 per acre-foot delivered within all of the districts. The cost of drain water was estimated to be $19.60 per acre-foot. The cost of groundwater is relative to the pumping lift where the cost is $19.60 plus $0.11 times the lift. Lift is estimated to be 20 feet for testing purposes, but in reality varies throughout the valley and under varying hydrologic conditions.

Historical Comparison

The model was tested for all of the districts for 2010 to 2015. The districts included in this model were only those that received surface water from the Boise River. The entire basin contains 12,679 defined Farm Agents and 276,679 Crop Agents. Figure 24 shows the Repast Agent Based model of the districts.

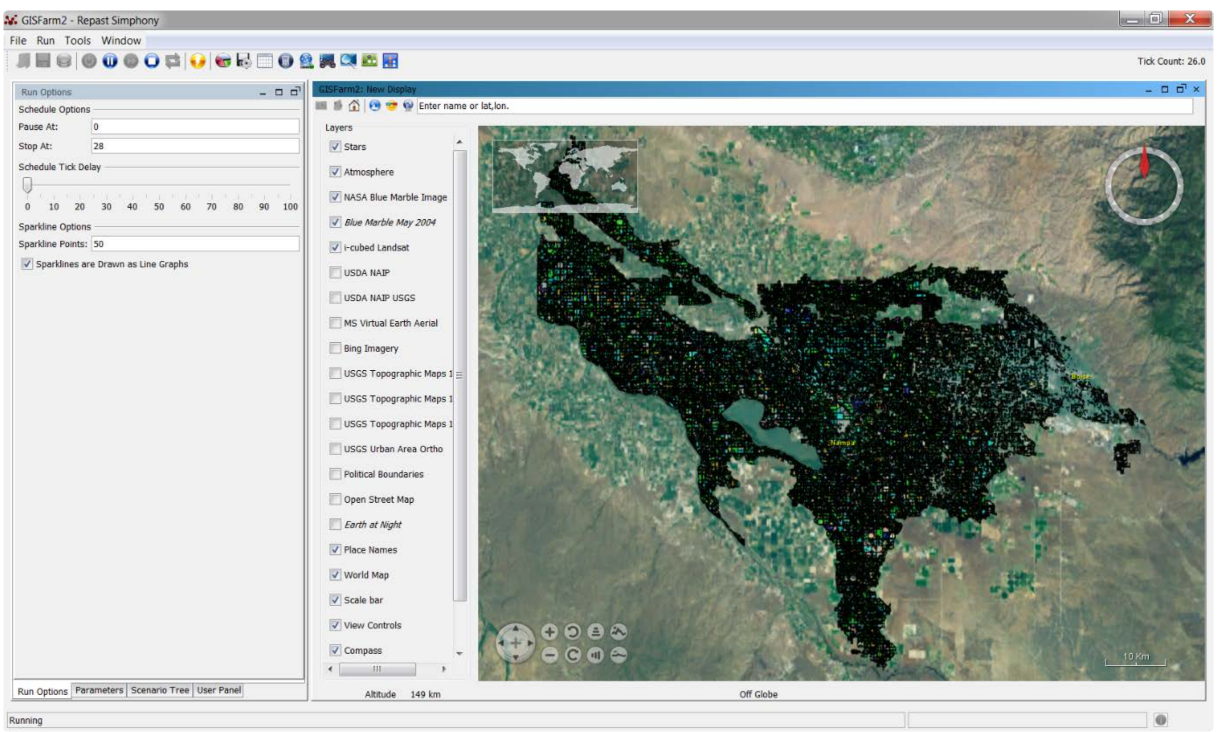


Figure 24: Image of all districts in the Repast Agent Based Model Software.

The maximum and minimum factor limits were adjusted for all of the districts to achieve the best possible matching of historical water needed along with total acres. Table 11 show the calibrated factor limits for the entire valley.

Table 11: Factor limits for the updating factor in the Update Probabilities Step.

	Beans	Corn	Hay	Herbs	Potatoes	Sugar Beets	Veg	Wheat
Max	10.4	10.5	1.5	1.7	1.1	10.6	1.1	30.7
Min	0.5	0.5	0.2	0.2	0.05	0.2	0.01	0.65

Model estimated annual water needed to irrigate the Crop Agent crops was compared to calculated historical annual water needed for the basin. The annual amount of water needed is calculated by multiplying calculated NIR values for 2010 through 2015 by the historical crop totals as measured in the CDLs. NIR values were calculated using weather input from the 2020 median climate scenario that begins in 2010.

Figure 25 shows the model simulated and historical annual water needed for the basin (top) and the percent residual (bottom). The amount of water needed was simulated to be within nine percent of the historical volume needed, which is about 40,000 acre-feet. The residuals are biased to the negative indicating that the model predicts a larger volume of water needed than historical.

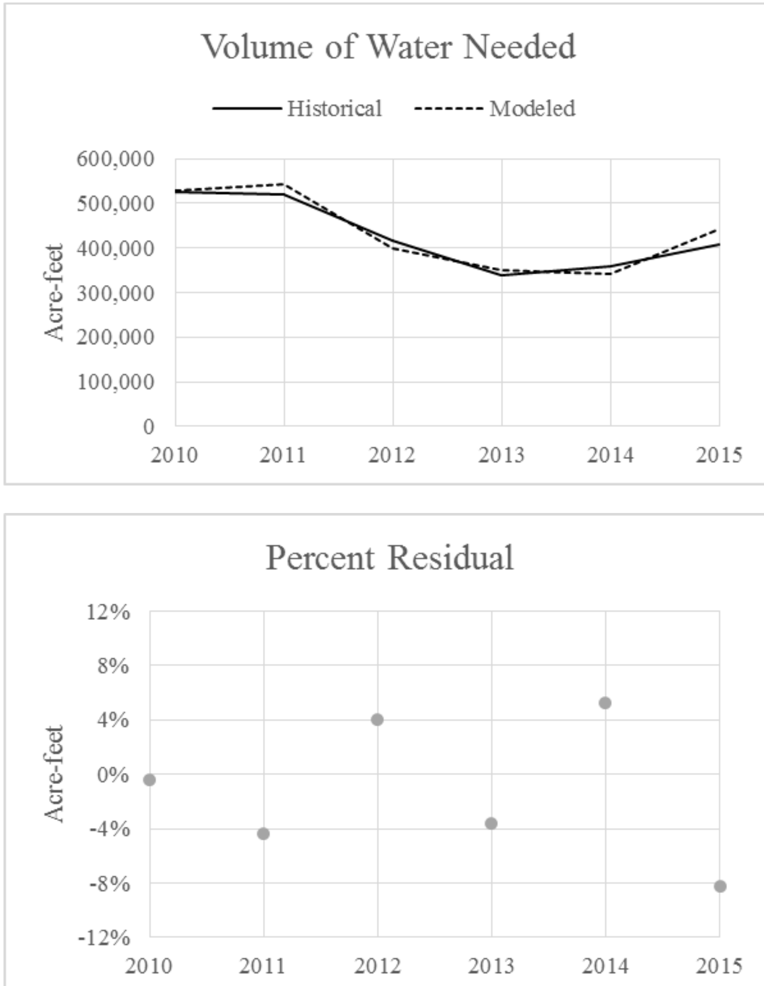


Figure 25: Model estimated and historical volume of water needed for the Boise Valley (top) and percent residual (bottom).

Previous methods of calculating NIR have refrained from using volumes and instead developed a weighted rate based on the distribution of crop acres within a particular area (Huntington, 2015). Figure 26 shows the weighted rate that is calculated in each year for the Boise Valley compared to the weighted rate calculated using the historical crop acre totals and the residual. The rates vary by less than 0.041 acre-feet per acre.

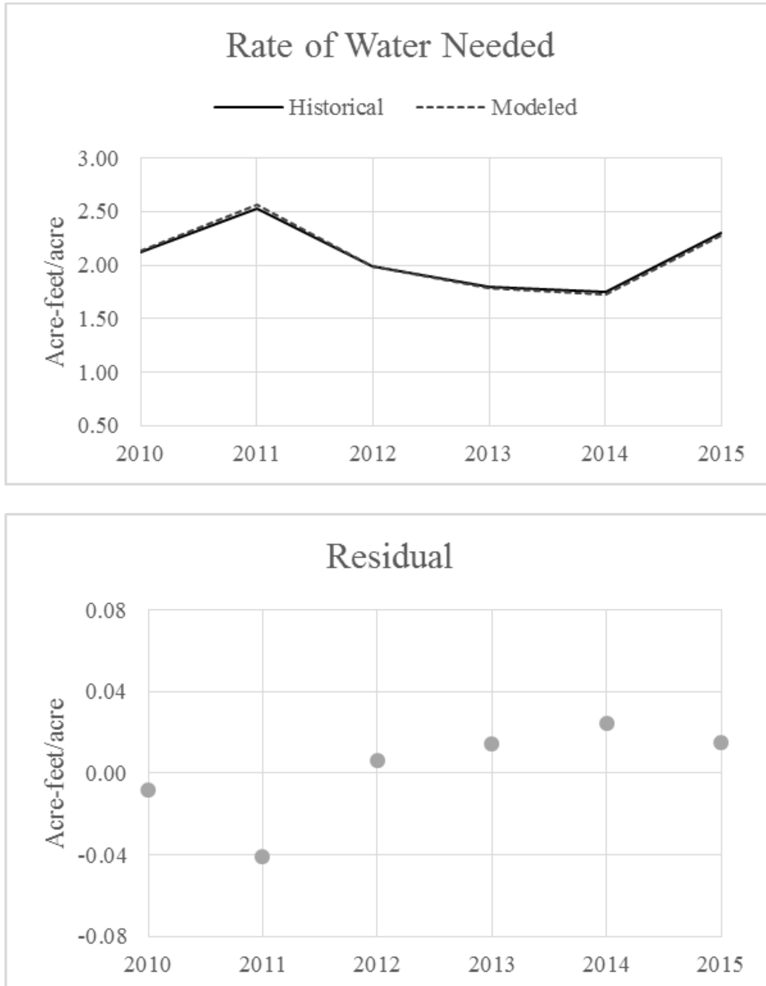


Figure 26: Model estimated and historical rate of water needed for the Boise Valley (top) and residual (bottom).

Model estimated crop totals were compared to historical totals for 2010 to 2015. On the aggregate, the model was able to estimate historical acres within three percent of the total acres in the Valley. Figure 27 shows the root mean squared of the model estimated acres divided by the total acres.

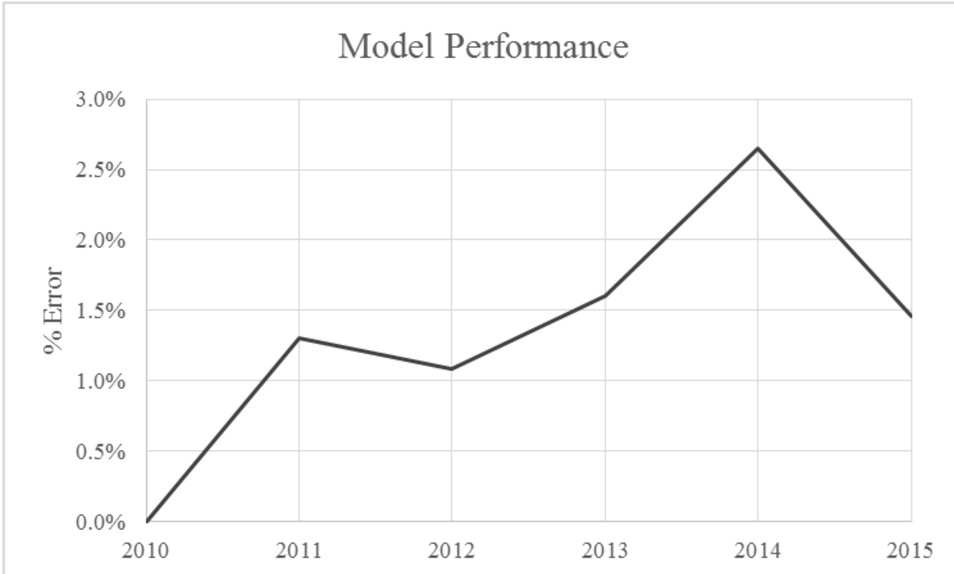


Figure 27: Root mean squared error of model estimated acres over total acres.

Figure 28 through Figure 35 shows the estimated and historical total acres and water needed for the individual crop types. Although the overall estimation of acres has reasonable error, the estimation of individual crop types is dependent on the relative number of acres for each type. The model does a better job estimating crop totals for the larger crop acreages, likely because there are more farmers making decisions to grow those crops and the aggregate is estimated well. The smaller acreage crops are not estimated as well likely because there may be only a few farmers that are selecting those crops to grow and their decision in any one year can drastically change the valley crop totals that are grown. The model generally predicts the trend of the crop totals, but does not exactly predict the totals in each year. Since the intent of the model is to determine the amount of water needed, it is not necessary to match the crop totals exactly as the amount of water needed appears to be interchanging among the crops. However, it provides interesting output that can be used to describe potential trends.

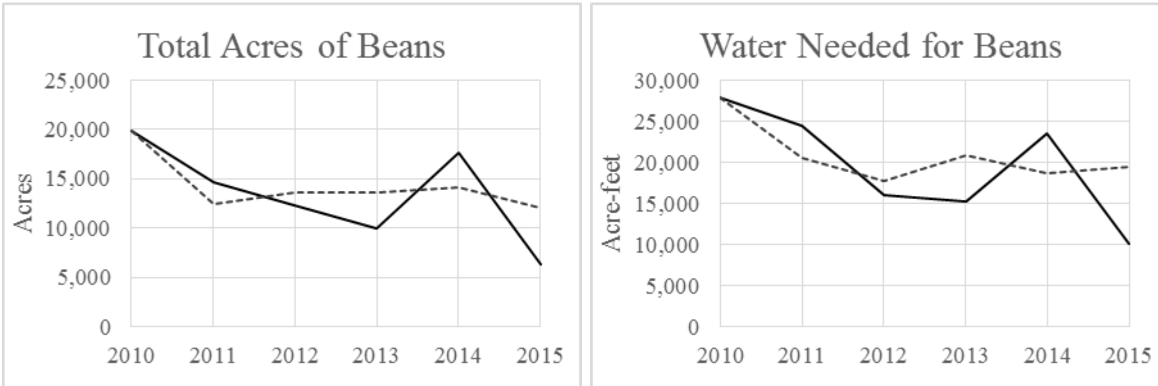


Figure 28: Model estimated (dashed) and historical (solid) total acres of beans (left) and water needed for corn (right).

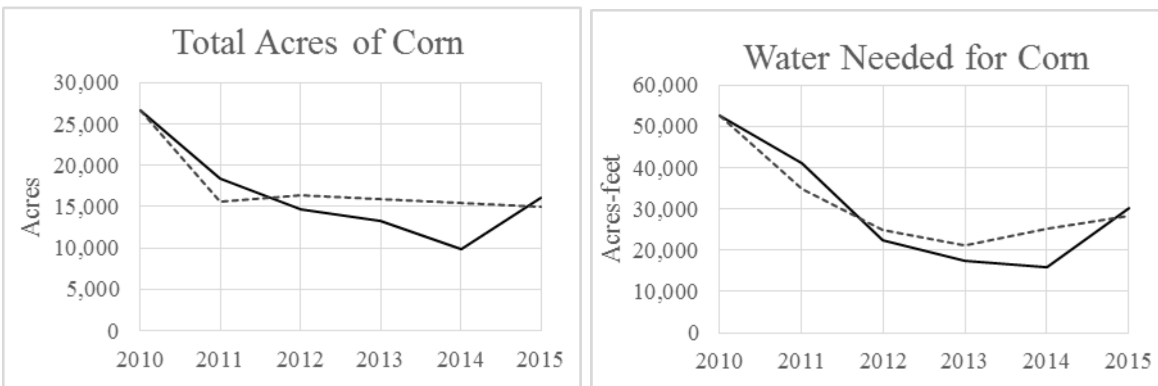


Figure 29: Model estimated (dashed) and historical (solid) total acres of corn (left) and water needed for corn (right).

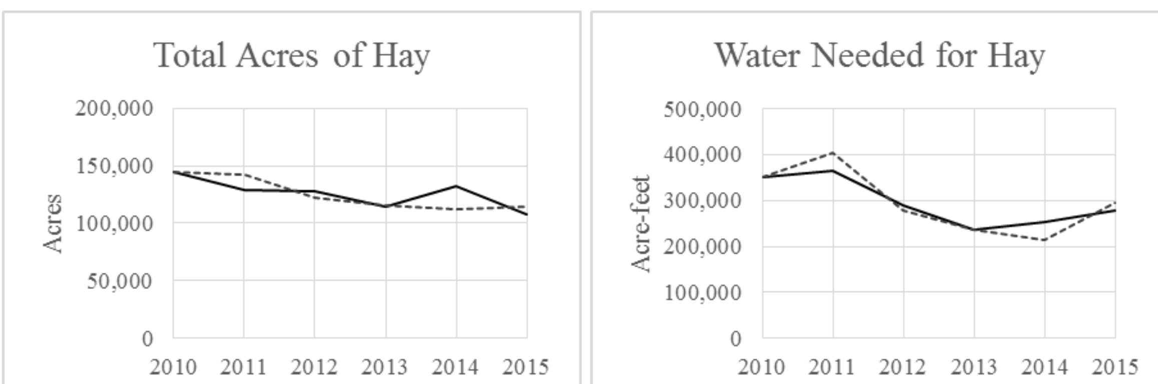


Figure 30: Model estimated (dashed) and historical (solid) total acres of hay (left) and water needed for hay (right).

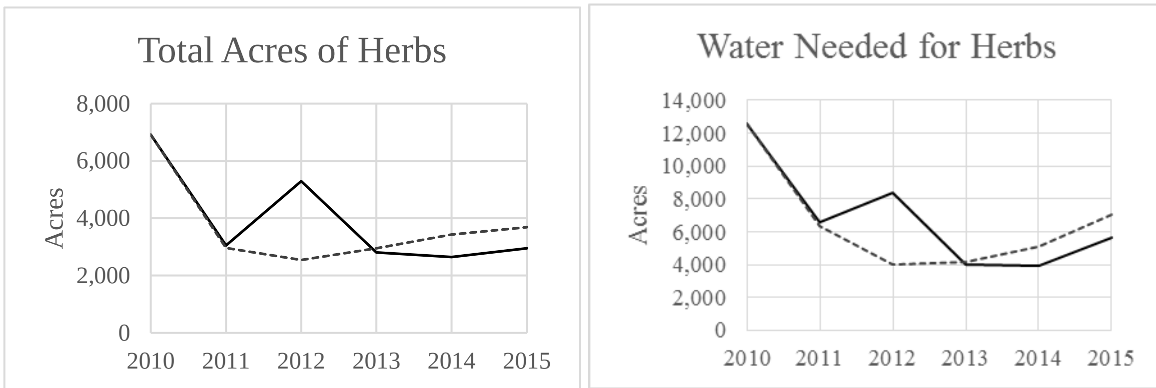


Figure 31: Model estimated (dashed) and historical (solid) total acres of herbs (left) and water needed for herbs (right).

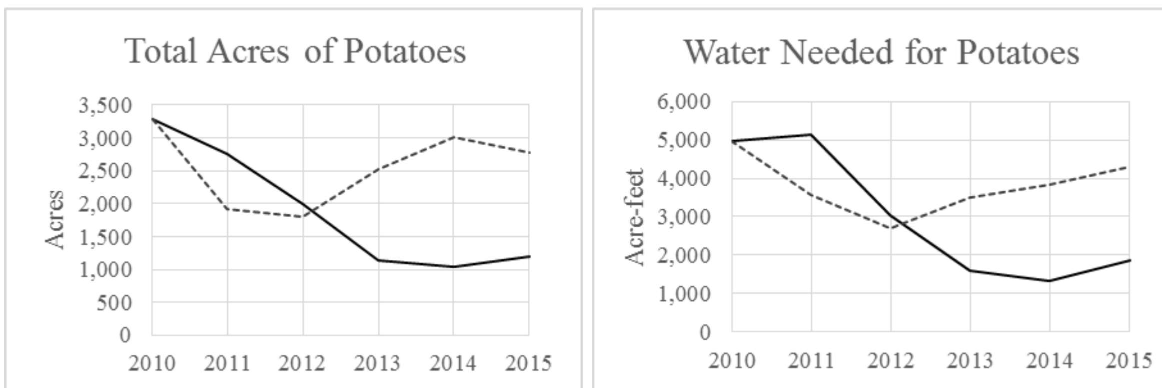


Figure 32: Model estimated (dashed) and historical (solid) total acres of potatoes (left) and water needed for potatoes (right).

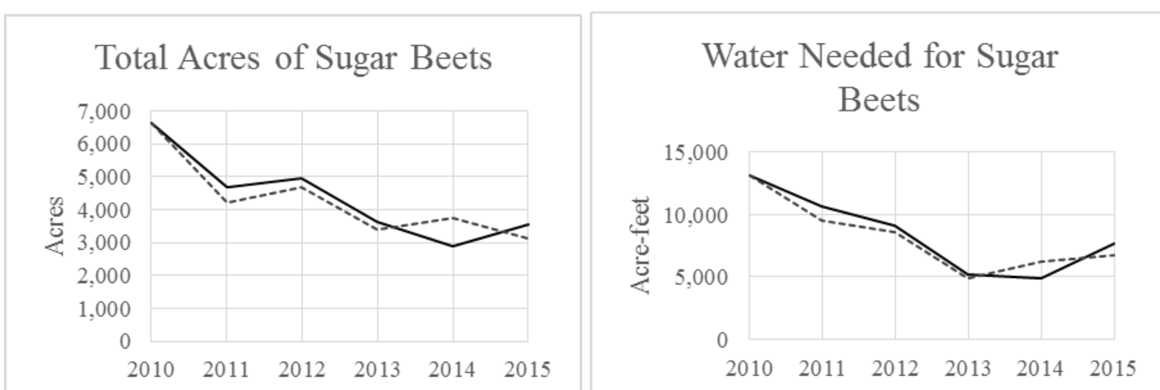


Figure 33: Model estimated (dashed) and historical (solid) total acres of sugar beets (left) and water needed for sugar beets (right).

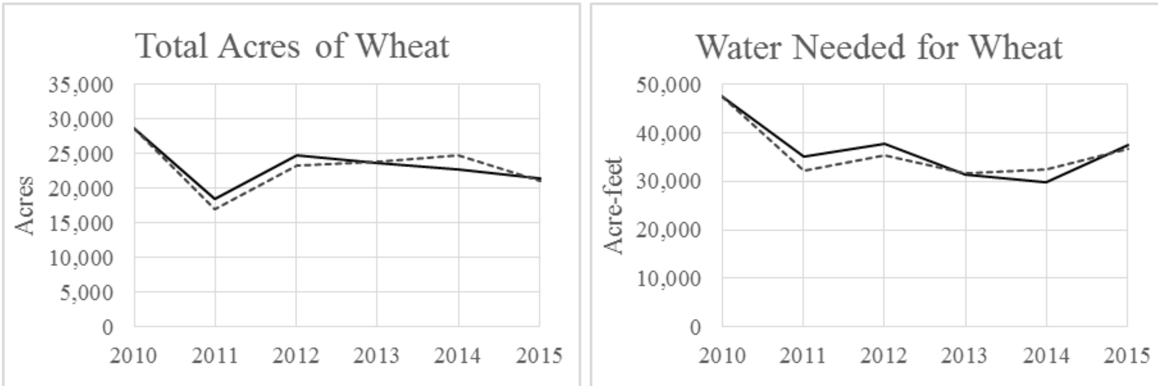


Figure 34: Model estimated (dashed) and historical (solid) total acres of wheat (left) and water needed for wheat (right).

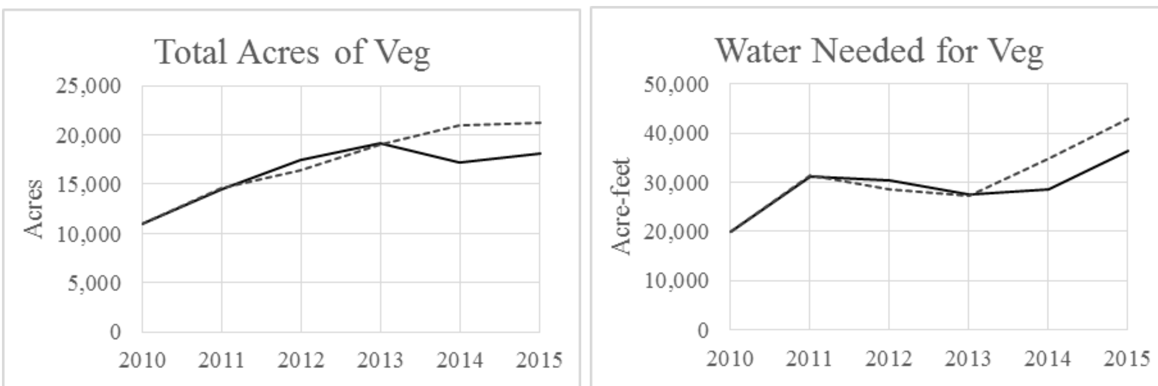


Figure 35: Model estimated (dashed) and historical (solid) total acres of vegetables (left) and water needed for vegetables (right).

Figure 36 shows model estimated developed and fallowed land for 2010 through 2015. The model is supplied with rates of development for each district so the plot on the left just confirms those rates are appropriate for the model period. The upward trend of fallowed land is predicted by the model, but the year to year variability is not.

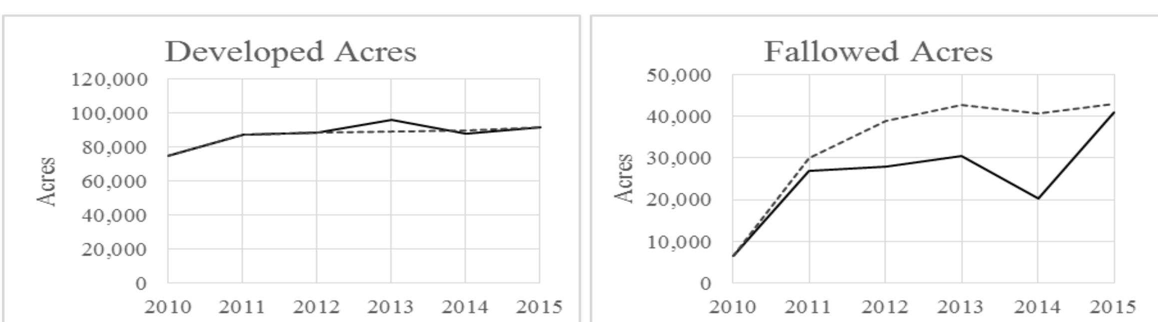


Figure 36: Model estimated (dashed) and historical (solid) total acres of developed (left) and fallowed (right) lands

The model can also be used to simulate the water needed and crop totals for individual districts. Results from the Pioneer Irrigation District and (lands served by the Phyllis Canal) and Boise Project Districts (lands served by the New York and Ridenbaugh Canals) for 2010 through 2015 are presented to show potential differences within districts. The PID contains 1,487 defined farms and 27,559 crop agents.

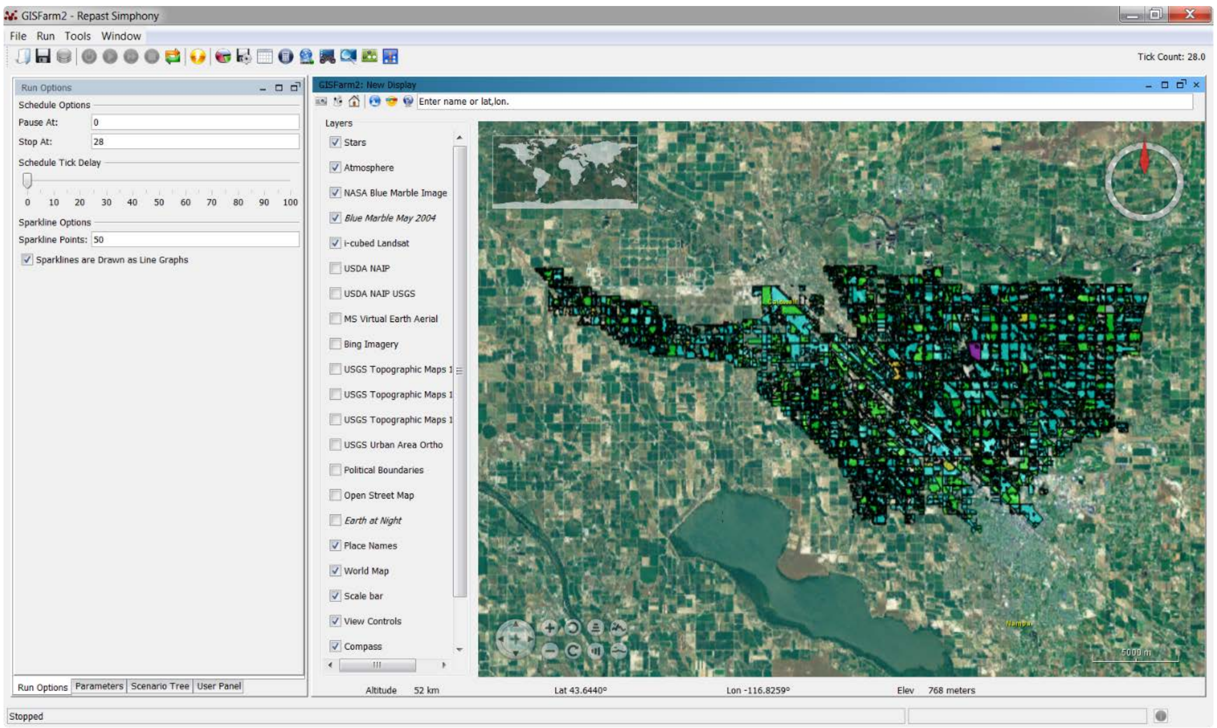


Figure 37: Image of the PID in the Repast Agent Based Model Software.

Figure 38 shows the historical and modeled water required to successfully irrigate the crops chosen in the PID using the same maximum and minimum factor limits as were used for all of the districts. Within the PID, the amount of water needed was estimated within 25 percent of the annual volume. Though this may seem like a large percentage, it is at most around 10,000 acre-feet which is about 2 percent of all of the water needed in the valley. The residual bias is negative indicating that that amount of water may be overestimated within this district.

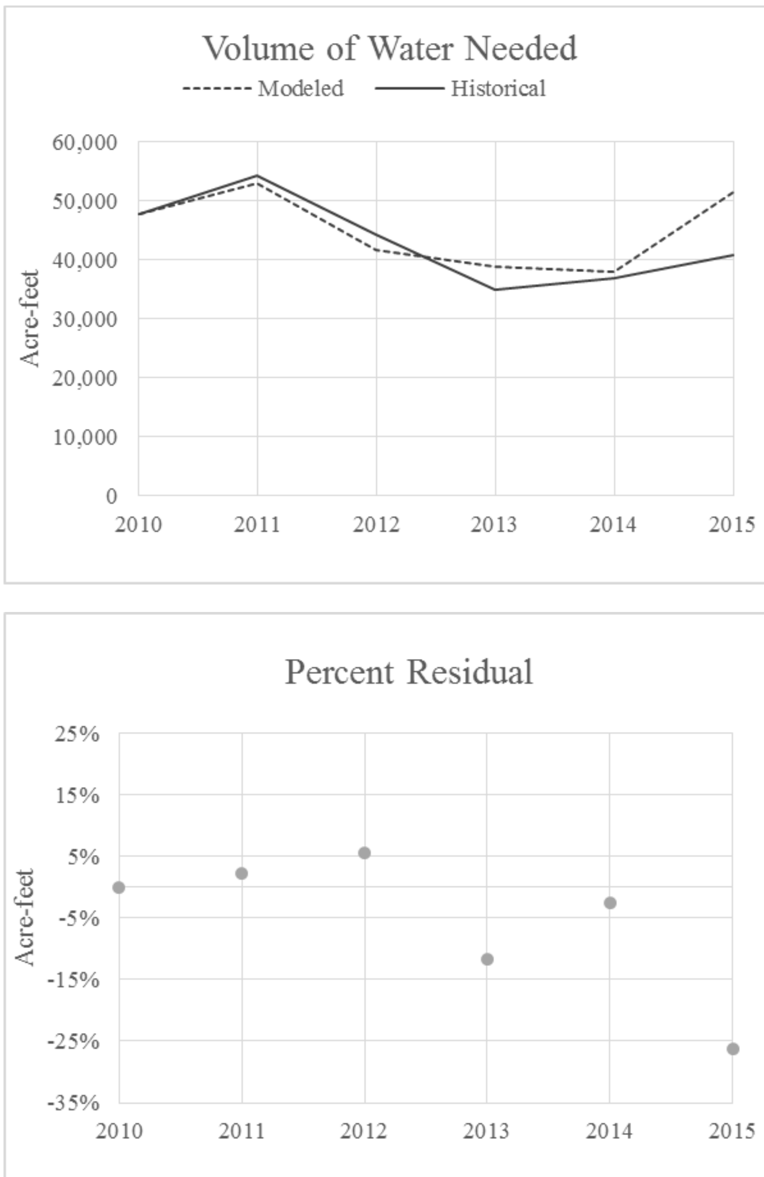


Figure 38: Model estimated and historical volume of water need for the PID (top) and percent residual (bottom).

Figure 39 shows the weighted rate of NIR for the PID. The rates vary by less than 0.2 acre-feet per acre.

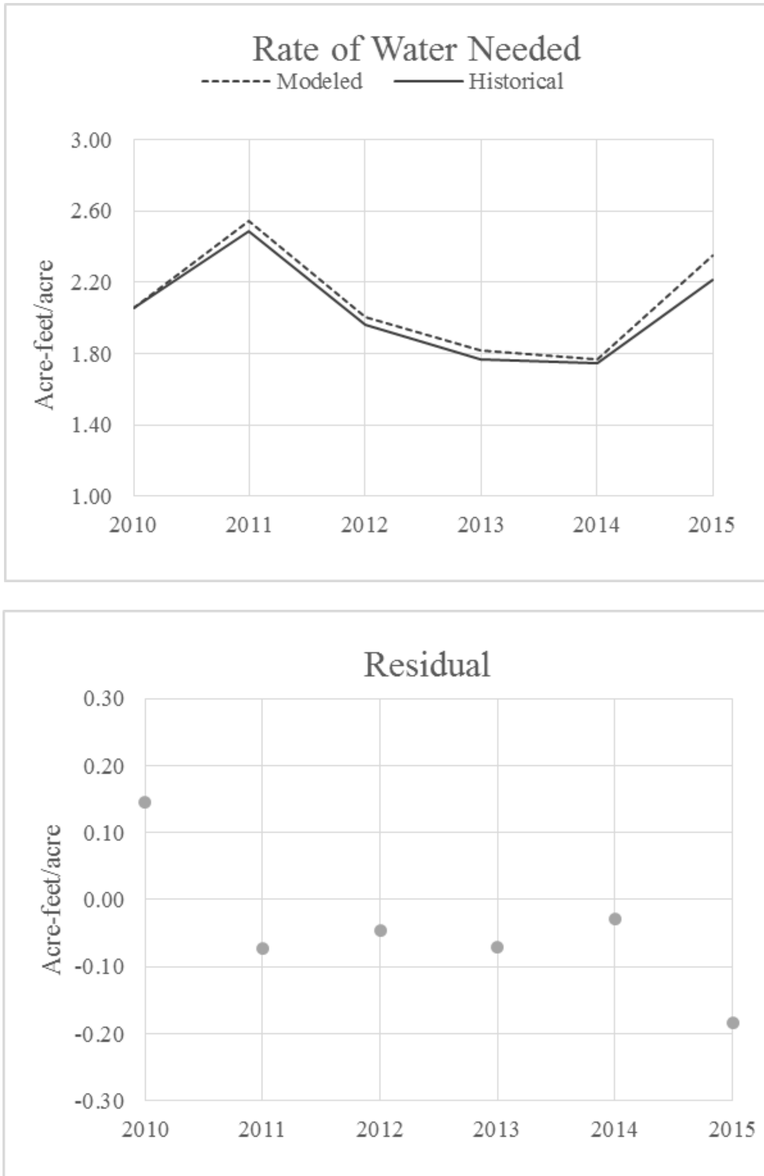


Figure 39: Model estimated and historical rate of water needed for the PID (top) and residual (bottom).

Model estimated crop totals were compared to historical totals for 2010 to 2015 for the PID district. On the aggregate, the model was able to estimate historical acres within 6.0 percent of the total acres in the district. Figure 40 shows the root mean squared of the model estimated acres for PID divided by the total acres in PID.

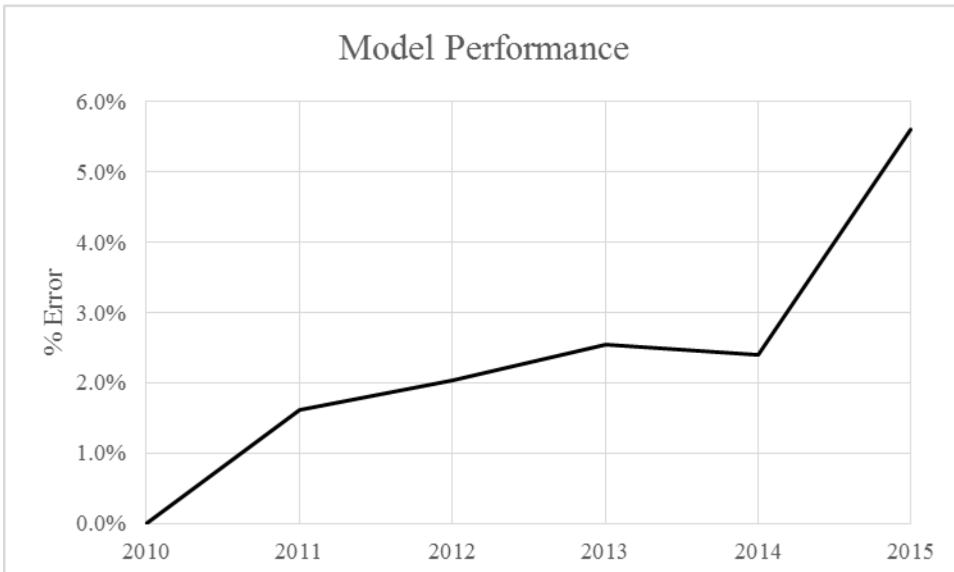


Figure 40: Root mean squared error of model estimated acres over total acres.

Figure 41 through Figure 48 show the estimated total acres and water needed for the historical crops grown. The model does not perform as well in the PID when predicting crop types, however, the results are still reasonable. The lesser degree of performance in this district is partially due to the minimum and maximum values that limit the amount a probability can change from one year to the next were set for the entire basin and not the individual district. It is also likely partially due to number of acres in the district are substantially less than the entire basin and the model does not perform as well when acreages are small.

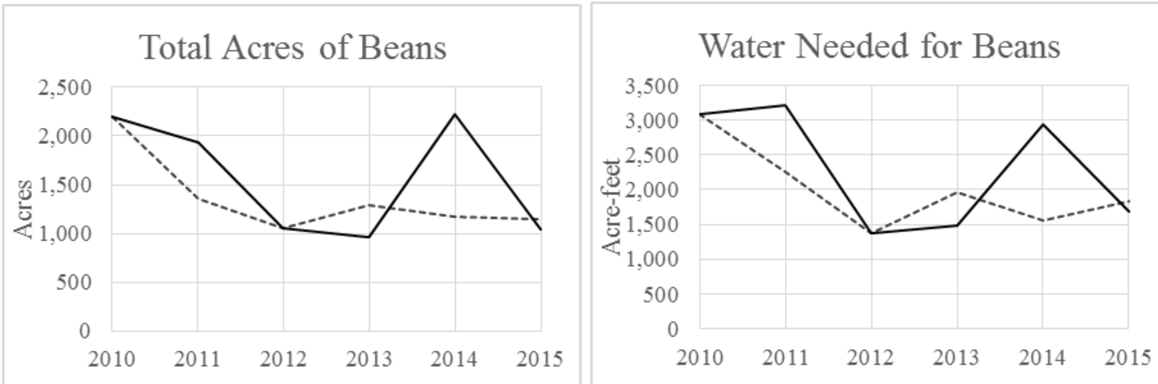


Figure 41: Model estimated (dashed) and historical (solid) total acres of beans (left) and water needed for beans (right).

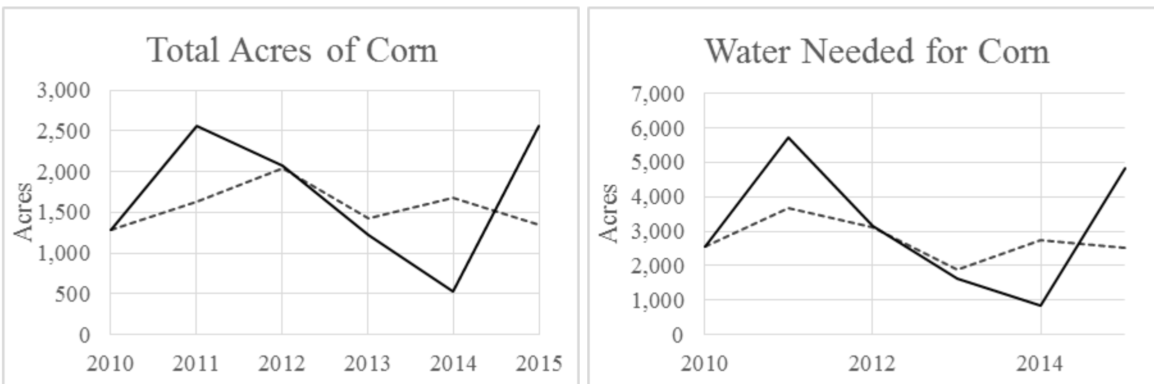


Figure 42: Model estimated (dashed) and historical (solid) total acres of corn (left) and water needed for corn (right).

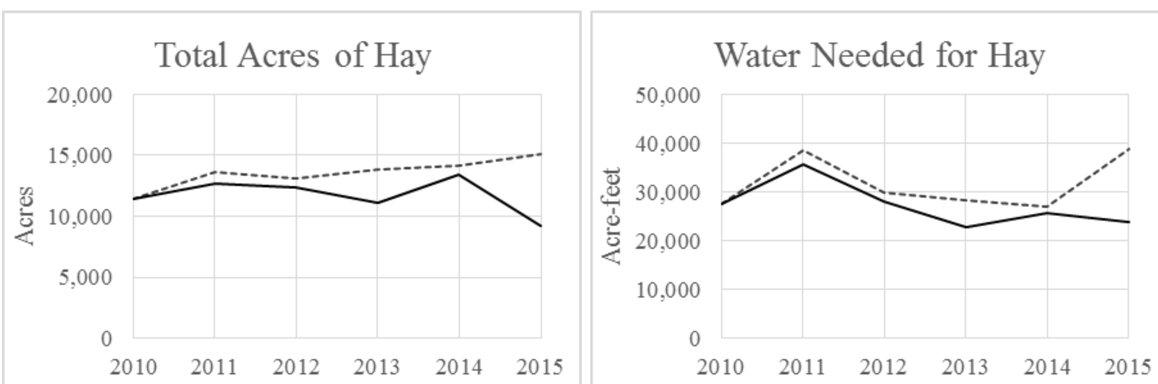


Figure 43: Model estimated (dashed) and historical (solid) total acres of hay (left) and water needed for hay (right).

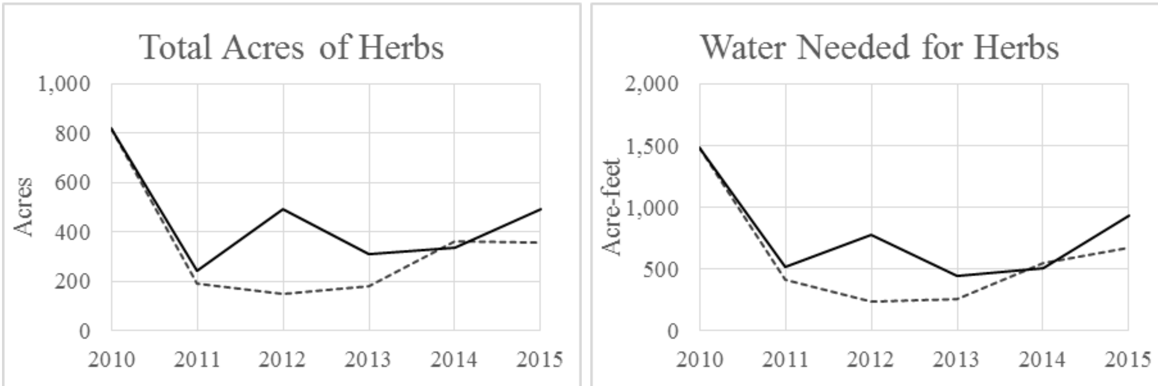


Figure 44: Model estimated (dashed) and historical (solid) total acres of herbs (left) and water needed for herbs (right).

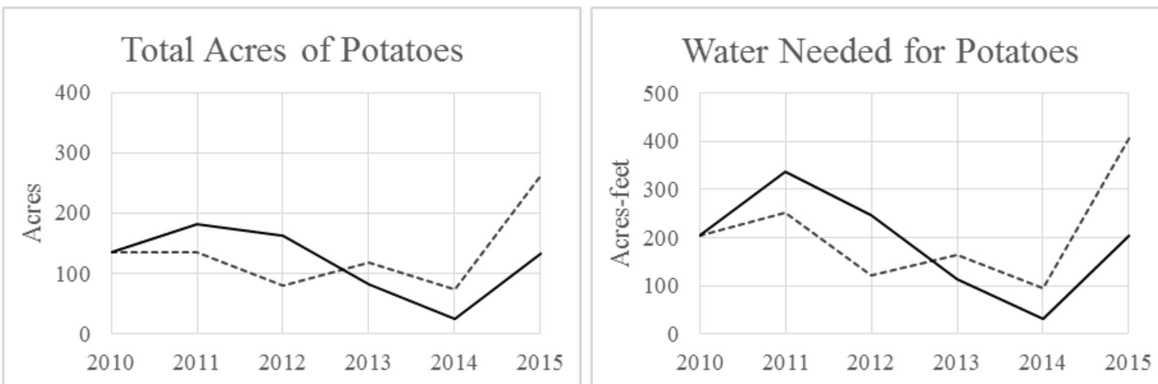


Figure 45: Model estimated (dashed) and historical (solid) total acres of potatoes (left) and water needed for potatoes (right).

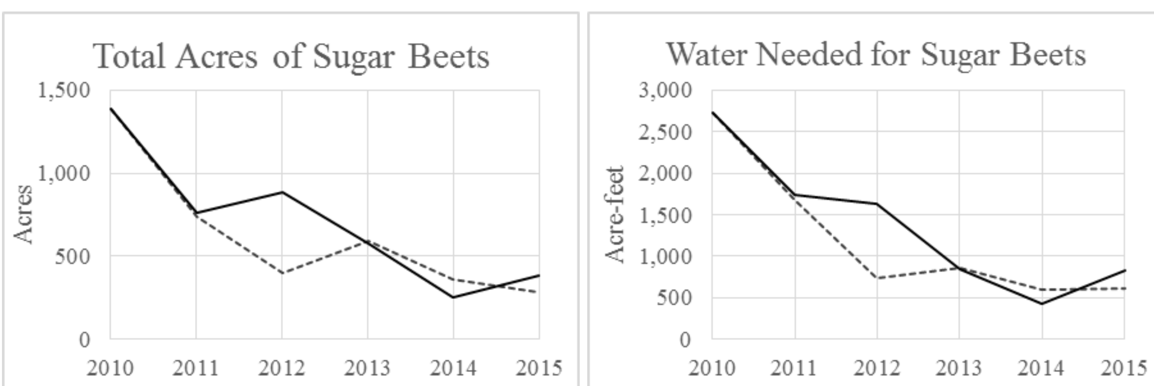


Figure 46: Model estimated (dashed) and historical (solid) total acres of sugar beets (left) and water needed for sugar beets (right).

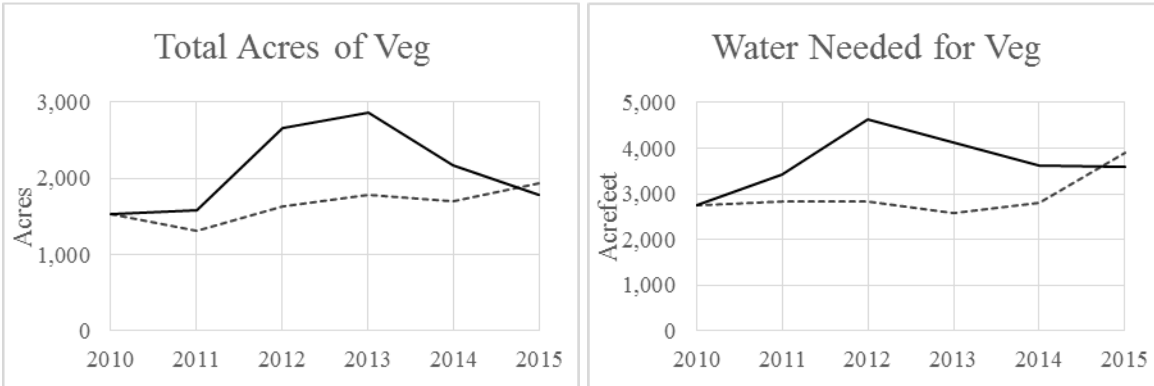


Figure 47: Model estimated (dashed) and historical (solid) total acres of veg (left) and water needed for veg (right).

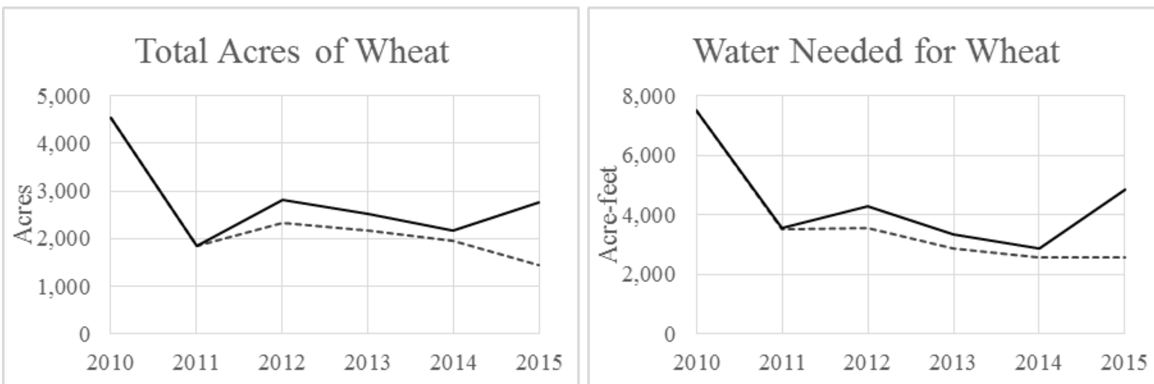


Figure 48: Model estimated (dashed) and historical (solid) total acres of wheat (left) and water needed for wheat (right).

Figure 49 shows the estimate of lands developed in the PID and the estimated fallowed lands. Since the rate of development is provided to the model, this plot confirms the rate is appropriate.

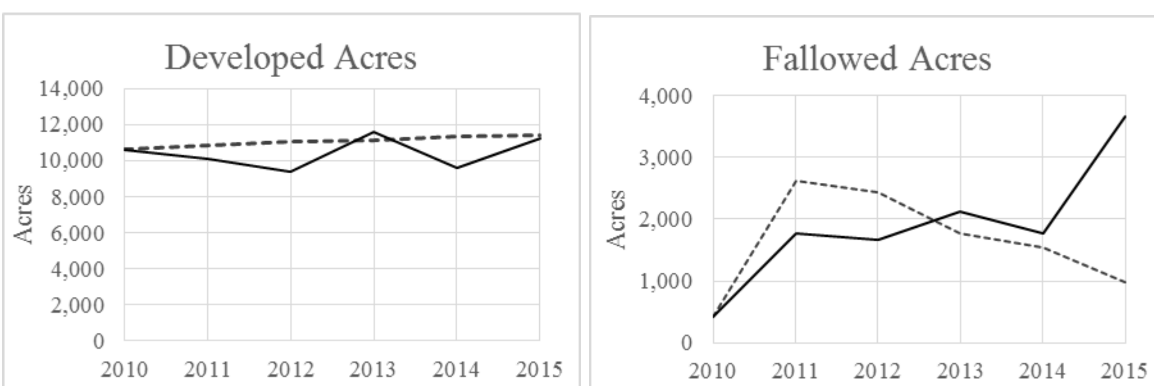


Figure 49: Model estimated (dashed) and historical (solid) total acres of developed (left) and fallowed (right) lands

The BPID contains 7,964 defined farms and 178,620 crop agents, and is the largest district in the model. Figure 50 shows the BPID as shown in the Repast Agent Based Model.

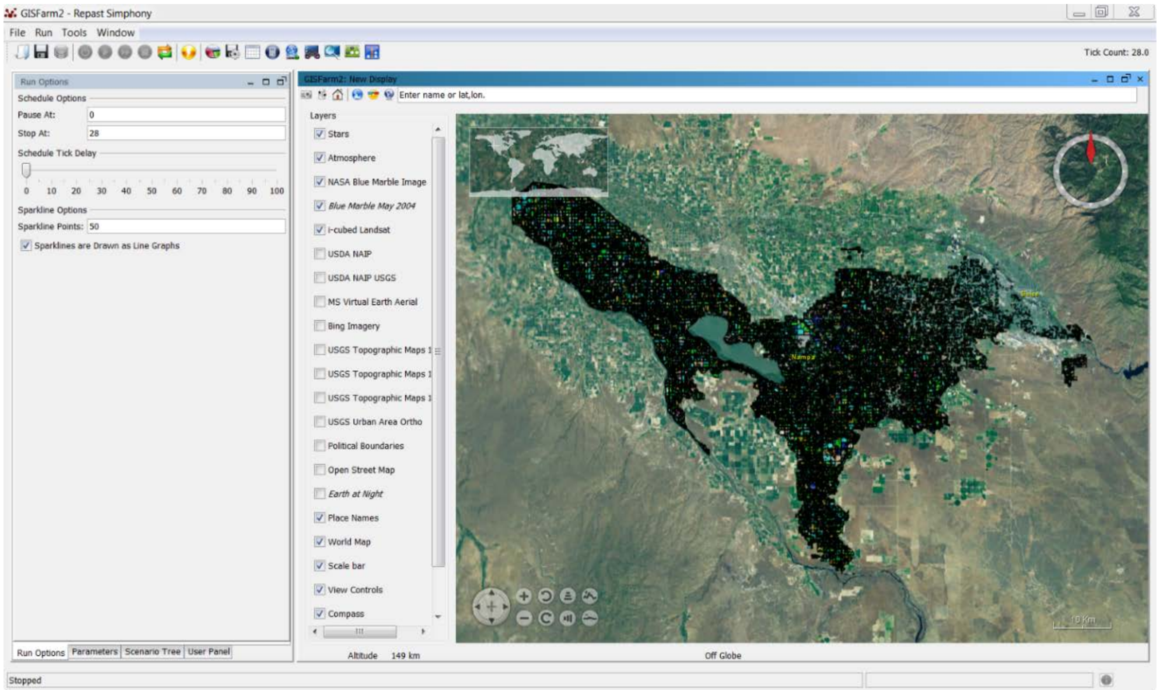


Figure 50: Image of the BPID in the Repast Agent Based Model Software.

Figure 51 shows the historical and modeled water required to successfully irrigate the crops chosen in the BPID. Within the BPID, the amount of water needed was estimated within 15 percent of the annual volume. The residual bias is balanced indicating that that amount of water is estimated well within this district.

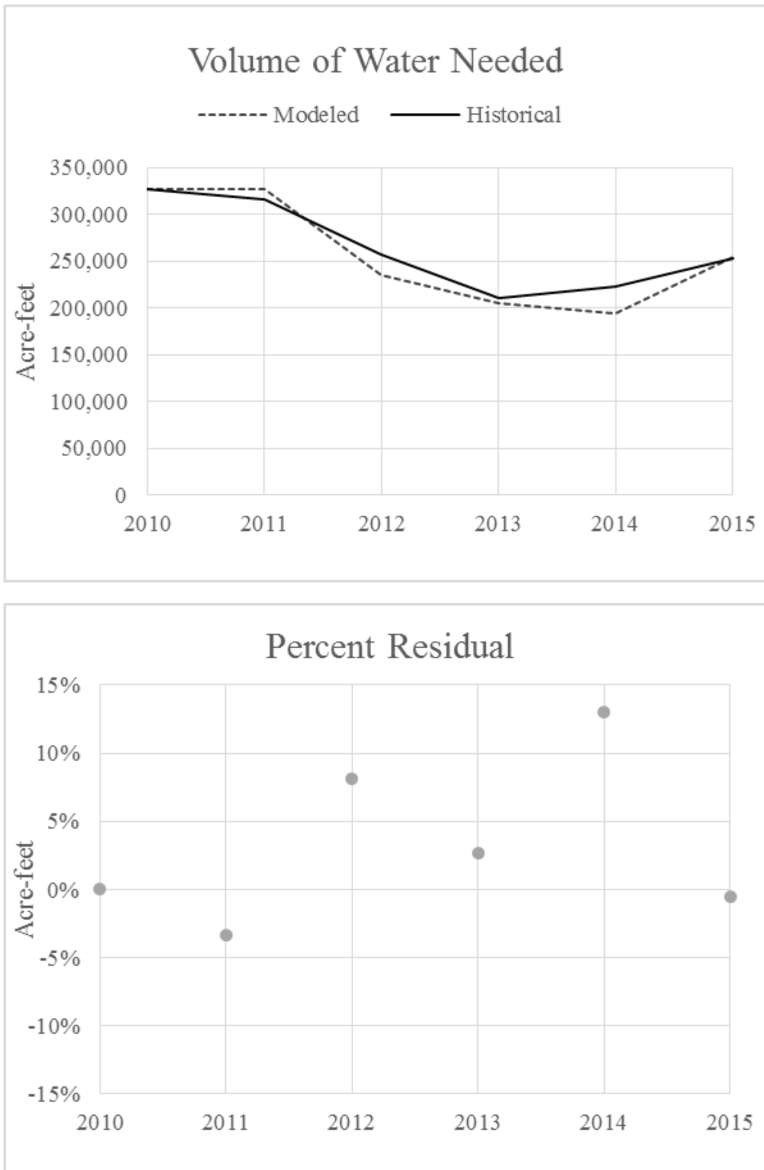


Figure 51: Model estimated and historical volume of water need for the BPID (top) and percent residual (bottom).

Figure 52 shows the weighted rate of NIR for BPID. The rates vary by less than 0.06 acre-feet per acre.

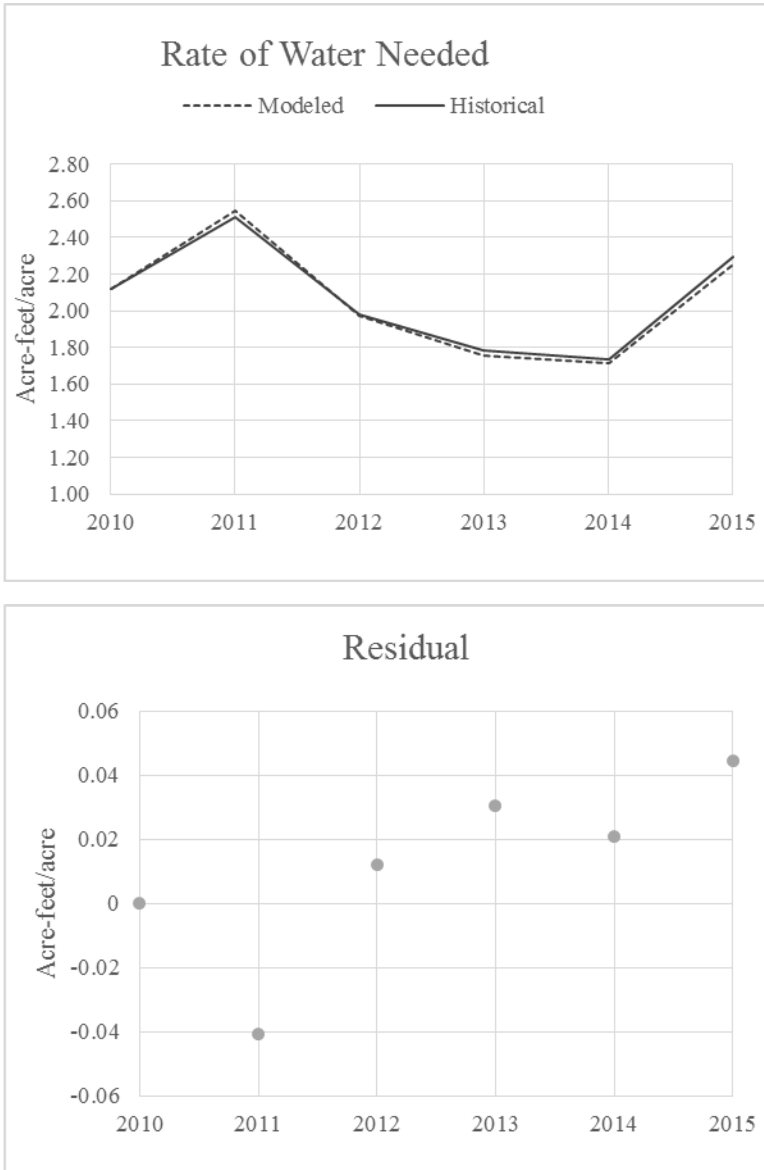


Figure 52: Model estimated and historical rate of water needed for the NIR (top) and residual (bottom).

Model estimated crop totals were compared to historical totals for 2010 to 2015 for the BPID district. On the aggregate, the model was able to estimate historical acres within 4.0 percent of the total acres in the district. Figure 53 shows the root mean squared of the model estimated acres divided by the total acres.

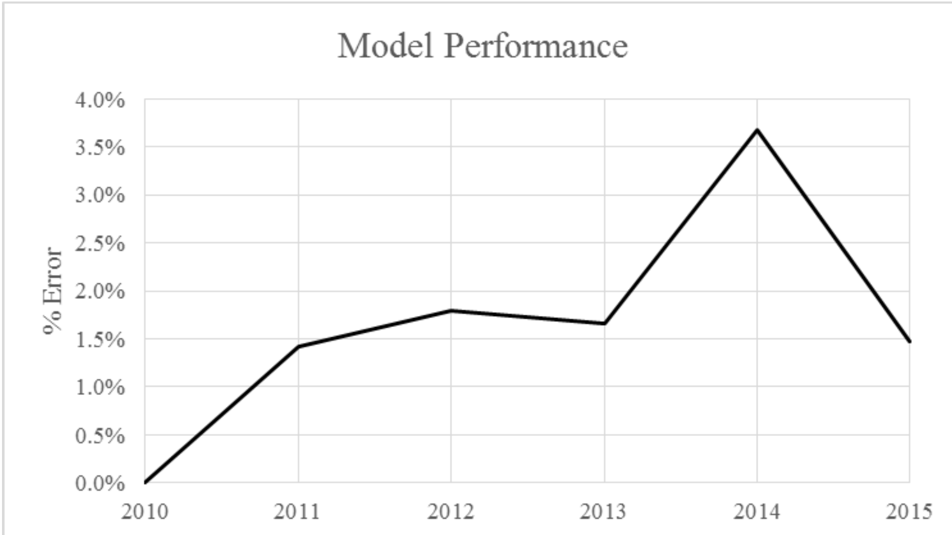


Figure 53: Root mean squared error of model estimated acres over total acres.

Figure 54 though Figure 60 show the estimated total acres and water needed for the historical crops grown. The model performs better in the BPID than in the PID district when predicting both the amount of water needed and the individual crop acres; however, it does not perform as well as for the entire basin. The BPID likely performs better because it is the largest district and has acreages that are more similar to the entire basin.

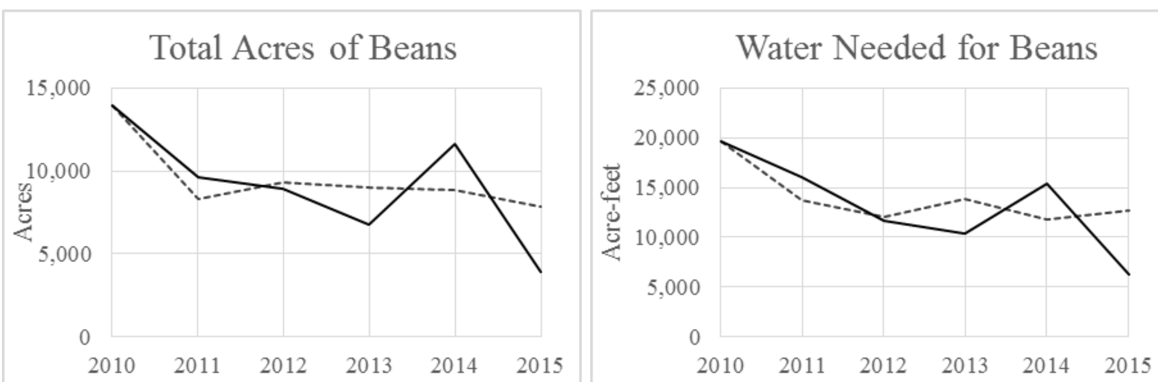


Figure 54: Model estimated (dashed) and historical (solid) total acres of beans (left) and water needed for beans (right).

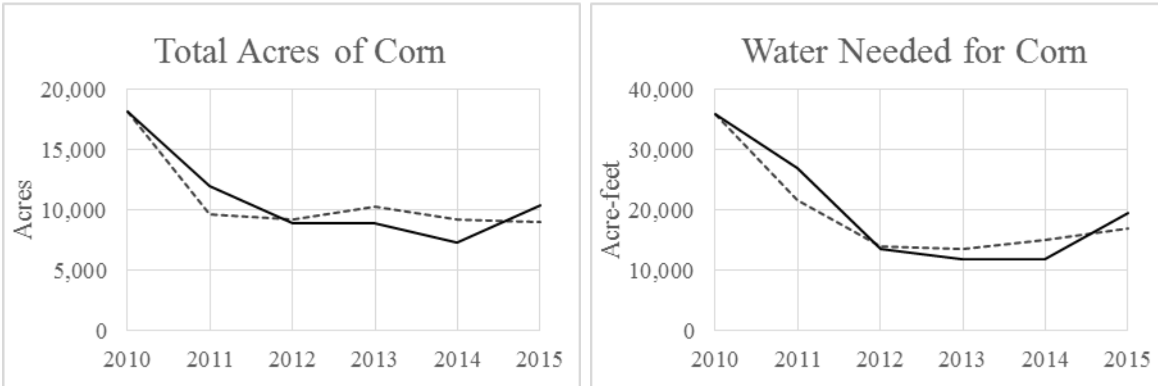


Figure 55: Model estimated (dashed) and historical (solid) total acres of corn (left) and water needed for corn (right).

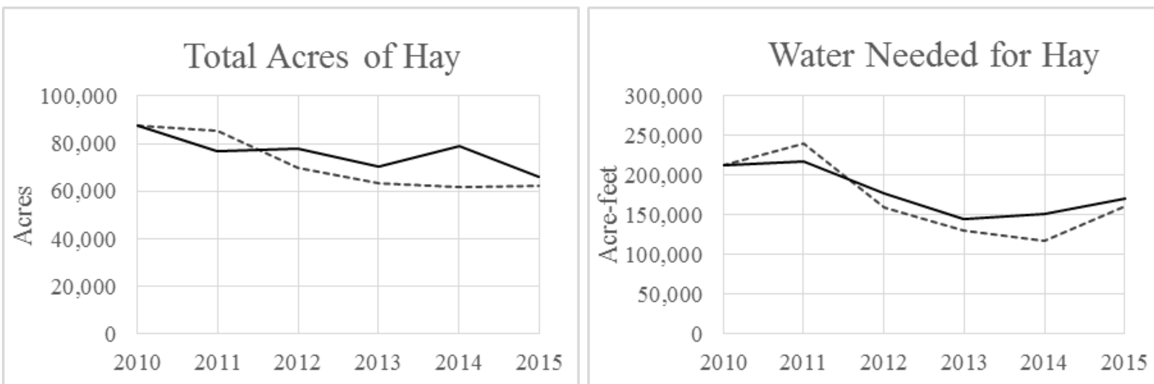


Figure 56: Model estimated (dashed) and historical (solid) total acres of hay (left) and water needed for hay (right).

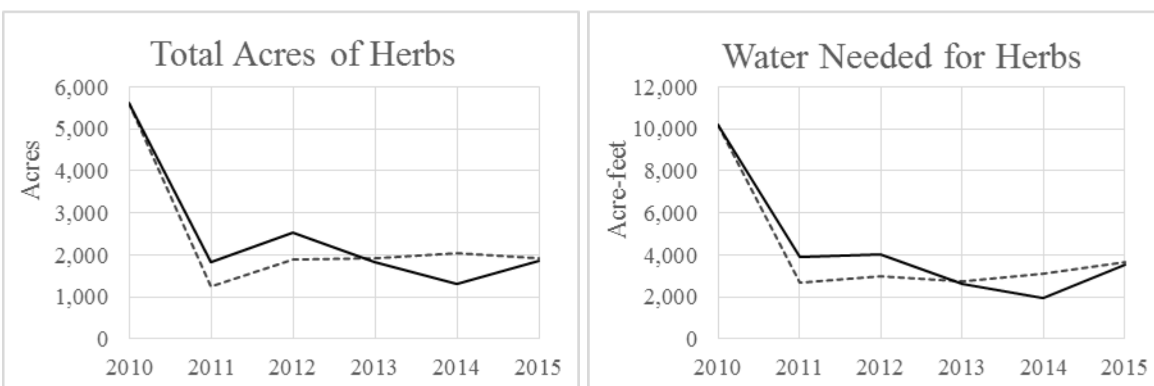


Figure 57: Model estimated (dashed) and historical (solid) total acres of herbs (left) and water needed for herbs (right).

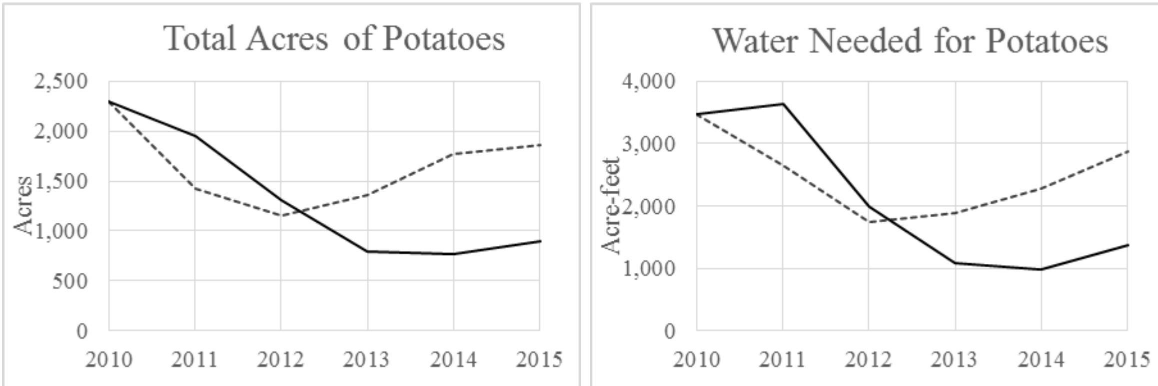


Figure 58: Model estimated (dashed) and historical (solid) total acres of potatoes (left) and water needed for potatoes (right).

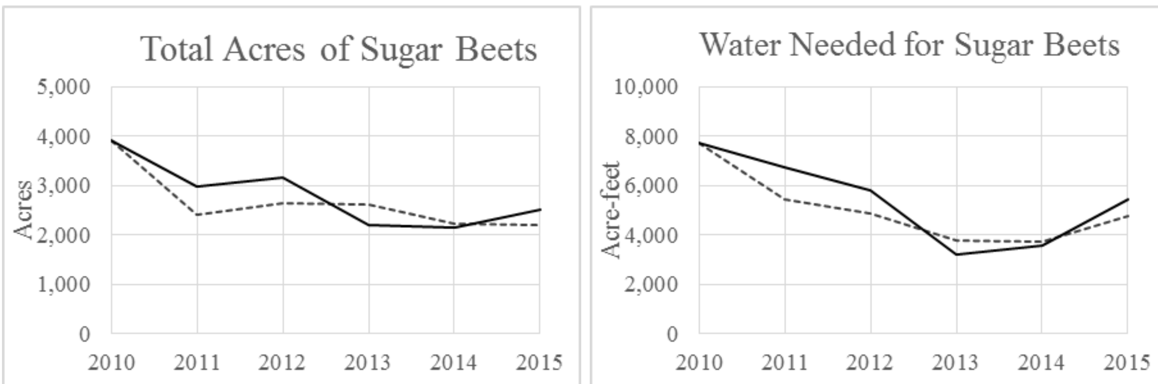


Figure 59: Model estimated (dashed) and historical (solid) total acres of sugar beets(left) and water needed for sugar beets (right).

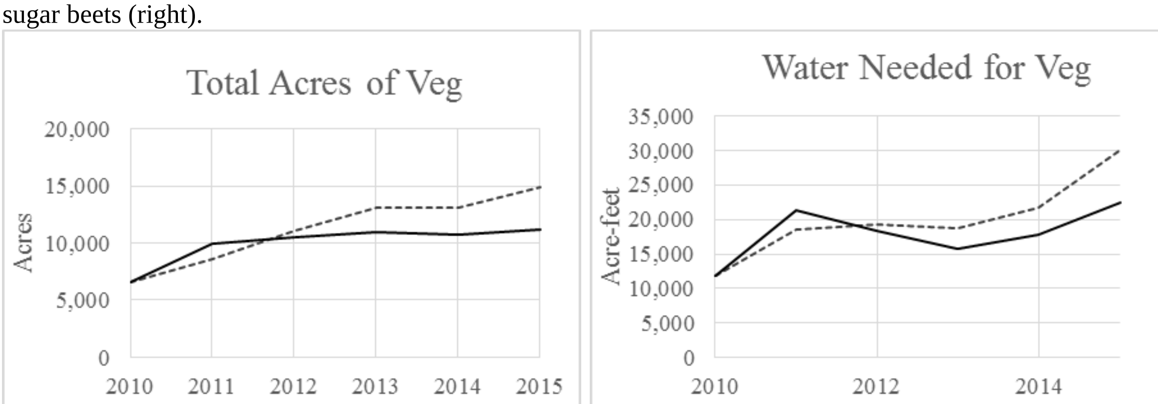


Figure 60: Model estimated (dashed) and historical (solid) total acres of veg (left) and water needed for veg (right).

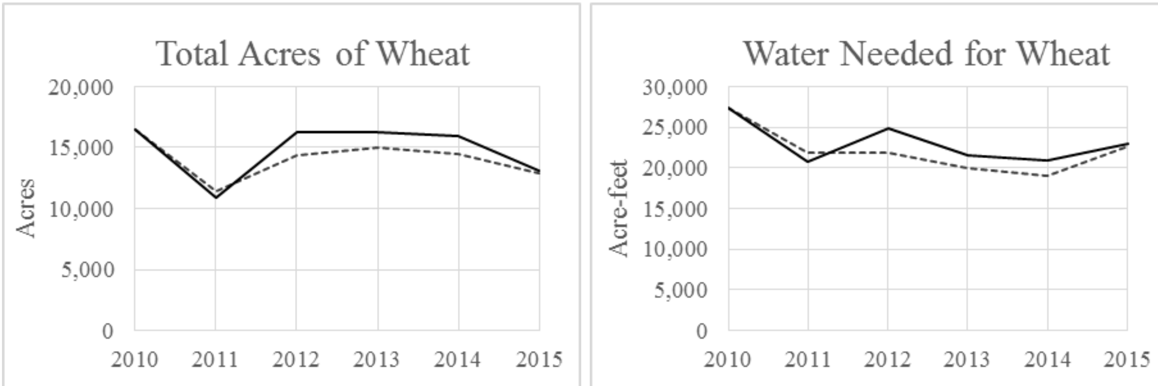


Figure 61: Model estimated (dashed) and historical (solid) total acres of wheat (left) and water needed for wheat (right).

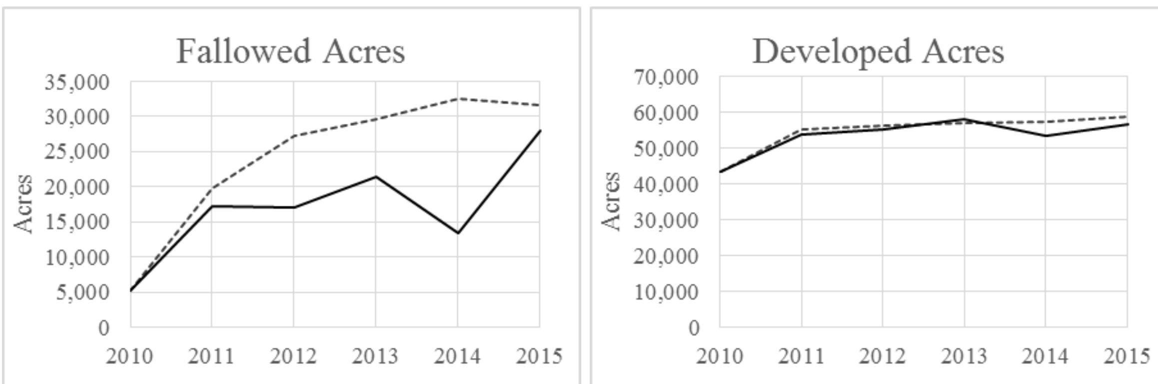


Figure 62: Model estimated (dashed) and historical (solid) total acres of developed (left) and fallowed (right).

Sensitivity Analysis

The driving factors of this model are the crop change tables that determine the probability a farmer will choose to grow one crop over another in a given year. Just as important are the crop change factors that adjust the probability tables after each year. Understanding the sensitivity of the parameters and assumptions are important to understanding the performance of the model.

The model is sensitive to the change factors that are applied to the crop change probabilities in each year, which is expected since the driving parameters in the model are the crop change probabilities. The factor limits help to constrain the change factors to ensure that the parameters do not change too quickly and are the main parameters used to calibrate the model. To illustrate the impact of the change factors, the factors were changed in the Phyllis district to better match the amount of water needed. Figure 63 shows the improved estimate of water needed for Phyllis with the factors shown in Table 12.

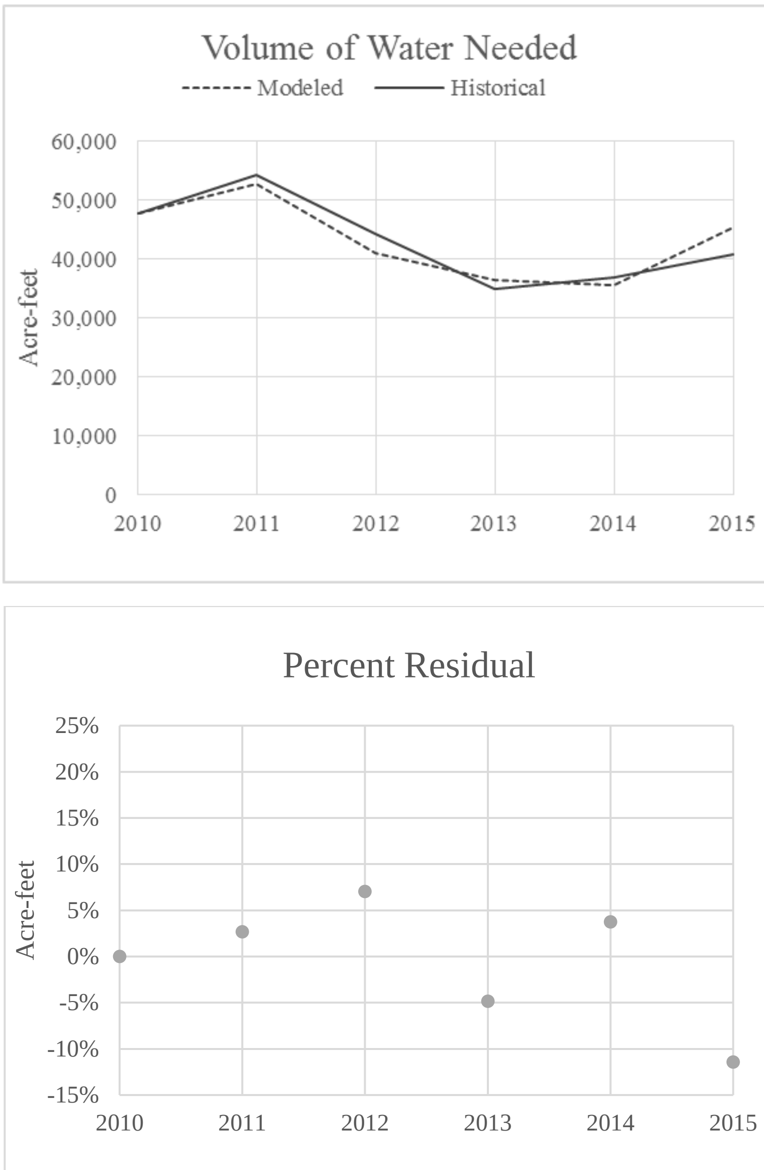


Figure 63: Model estimated and historical volume of water need for the PID (top) and percent residual (bottom) after adjusted factor limits.

Table 12: Adjusted factor limits for the updating factor in the Update Probabilities Step for the PID.

	Beans	Corn	Hay	Herbs	Potatoes	Sugar Beets	Veg	Wheat
Max	10.7	20.5	1.2	2.9	1.1	15.6	1.05	30.7
Min	0.6	0.01	0.01	0.2	0.05	0.2	0.01	0.75

By adjusting the factor limits, the percent difference in the volume of water calculated could be reduced from 25 percent to 12. Some of the changes were by orders of magnitude and some were smaller; however, they all resulted in a better calibration of the PID water needed.

A test was performed to change the cost of groundwater and surface water independently to determine the sensitivity of the total water needed. Decreasing the cost of groundwater by dividing the 20 foot pumping depth by 10 resulted in a minimal change in water needed. Increasing the cost of groundwater by multiplying the pumping depth by 10 resulted in a decrease in water needed by as much as 4.7 percent. Increasing the cost of surface water by a factor of ten resulted in a decrease in the amount of water needed by as much as 30 percent. Since decreasing the cost of surface water is an unlikely condition, it was not tested. The amount of water needed is also very sensitive to the rate of change to developed lands. Increasing the rate of development by ten percent resulted in an increase of up to 32 percent of water needed.

The results of the individual sensitivity tests were within the bounds of expected results and showed that the model reacted to the changes as expected.

Simulation of Water Needed

Figure 64 shows the estimated amount of water needed for the 28 year simulation period using the 2020 future climate estimates of net irrigation water requirement for each crop and available surface water for all of the districts. It can be seen that there is a decline in the total amount of water needed for the Boise Valley within the 28 year period of nearly 100,000 acre-feet. The decline in water needed appears to steadily decrease for about half of the simulation and then reaches a dynamic equilibrium. The amount of hay appears to be a driving factor in the amount of water needed since it is the most abundant crop category and it is the crop that requires the most water (the hay category includes pasture and other grass lands). Vegetables and Potatoes increase the amount of acres grown and the remaining crops remain similar to historical crop totals.

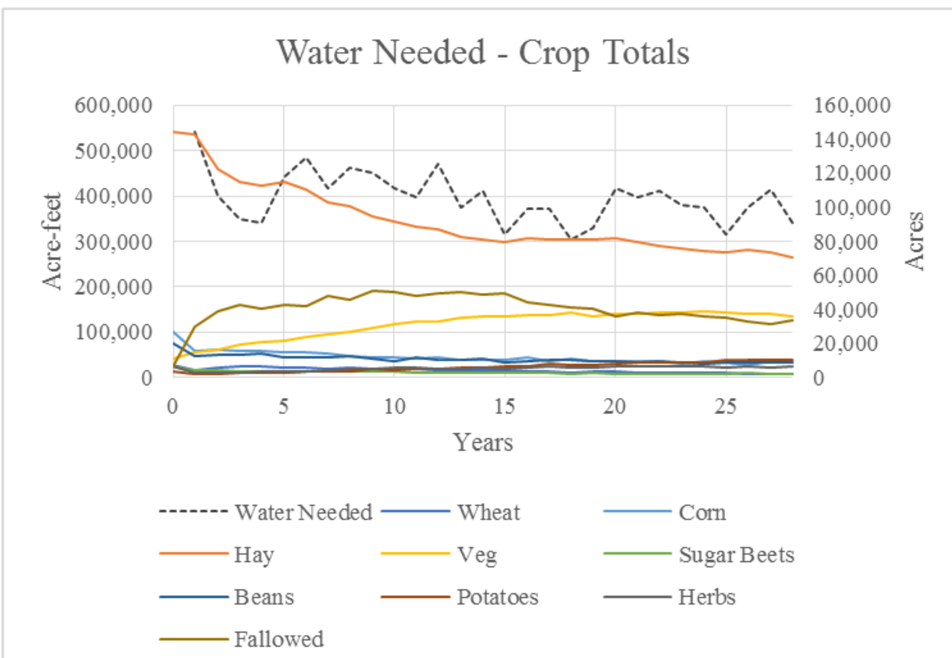


Figure 64: Water Needed for all crop in Boise Basin along with crop acres.

Figure 65 shows the cost of water per acre-foot along with the volume of water needed and can be used in combination with Figure 64 to understand the interplay between the cost of water and the choice of crops grown. The cost of water closely followed the amount of water needed. For years one through four, the high cost of water causes a substantial increase in fallowed lands; most of the lands formerly grew Hay. This caused an overall decrease in the amount of water needed and therefore the cost of water decreased.

In year five, the lower cost of water caused a slight increase in the amount of Hay grown, which caused an increase in the amount of water needed and the cost of water. In year five, an increase in the amount of Vegetables and Potatoes starts to emerge as a result of their higher profit potential (see Table 10).

For years five through twelve, the cost of water remained relatively constant between twelve and 14 dollars per acre-foot. Higher profit potential crops continued to increase as the acres of Hay decreased, which over time lead to a decrease in the need for water, as Hay has the highest NIR. As the need for water decreased in years twelve through 18, the cost of water decreased. When the cost of water was below 11 dollars per acre-foot, the number of acres of Hay stabilized for about 5 years. In year 20, the cost of water started to increase again and the number of acres of Hay started to decrease again.

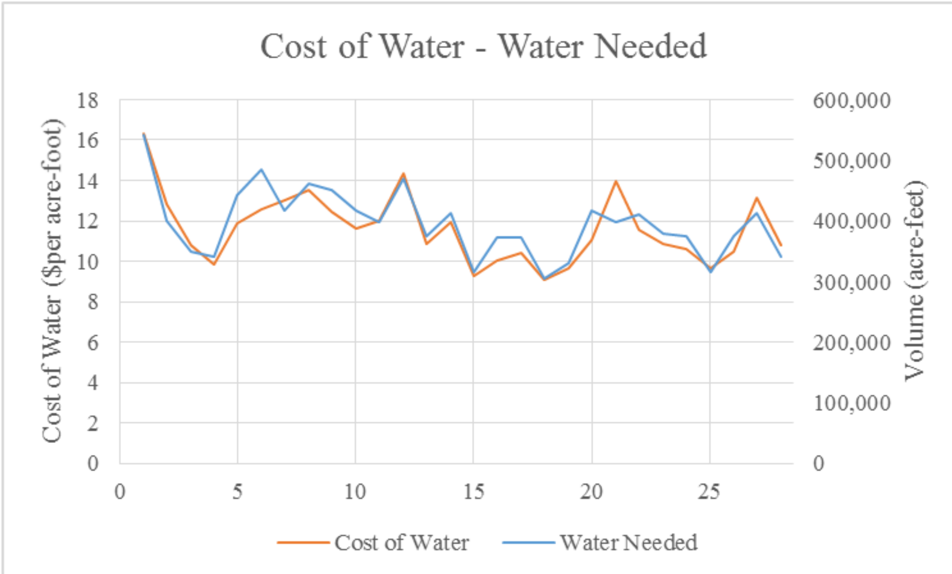


Figure 65: Cost of water and volume of water needed for entire basin.

Figure 66 shows the water needed for the PID along with the individual crops grown for the 28 year simulation, and Figure 67 shows the amount of water needed along with the cost of water. The results for the PID are of interest because the PID has a much lower cost of water due to its access to drain water. The access to drain water also keeps the cost of water relatively constant. The PID is one of only two districts that have access to drain water in this simulation.

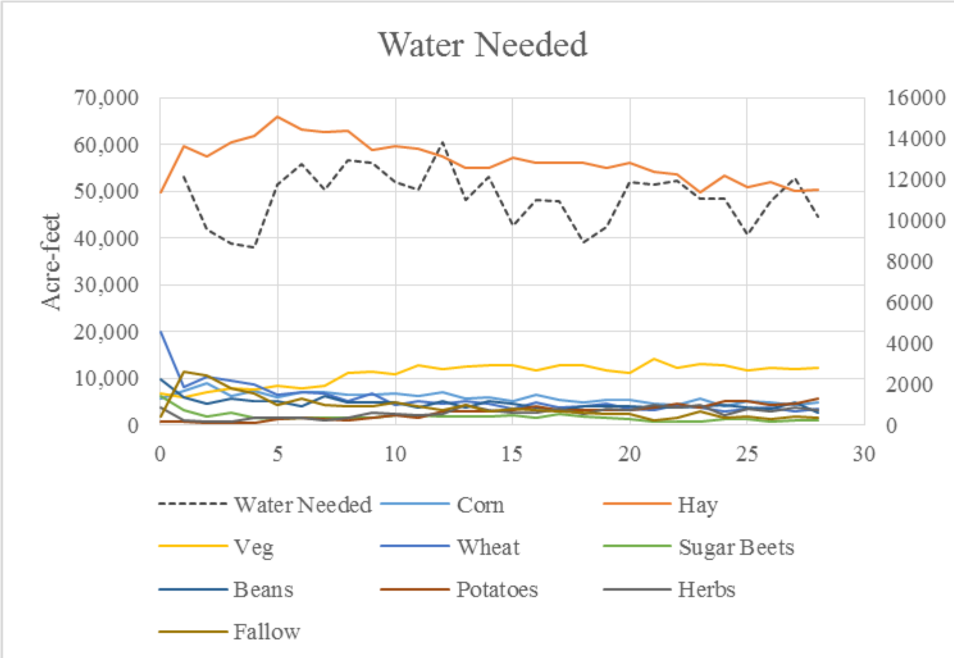


Figure 66: Water Needed for all crop in the PID along with crop acres.

Since the cost of water remained relatively constant throughout the simulation, the reduction in acres of Hay was much less pronounced than what was seen for the entire basin. However, there is still a decrease in Hay over time as the higher profit potential crops started to trend upward and lands continued to develop.

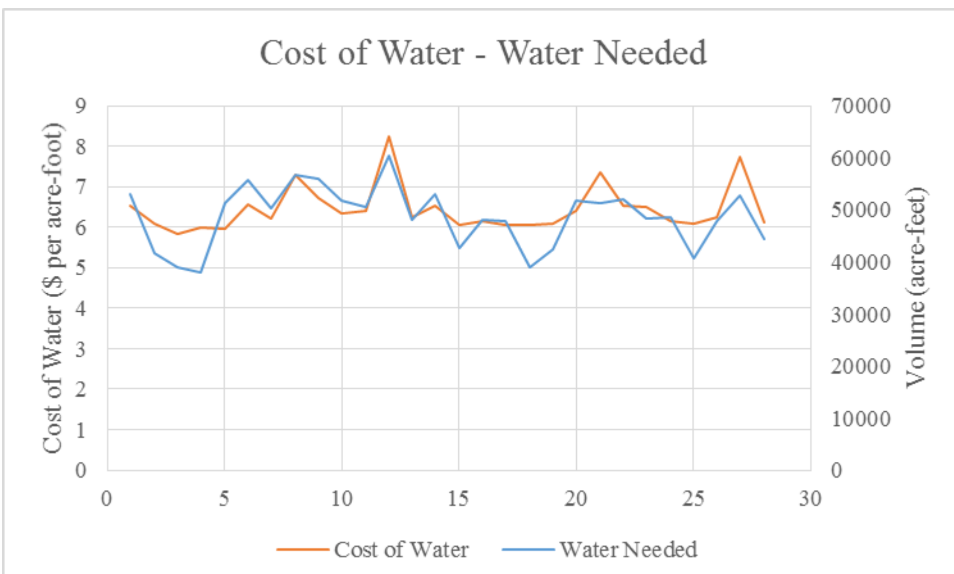


Figure 67: Cost of water and volume of water needed for the PID.

Using the 2080 median NIR and available surface water from the RiverWare model, future estimates of water needed and crop totals were estimated starting with the crop totals in 2010. Figure 68 shows the estimated water needed along with the crop totals. The amount of water decreases over time, as in the 2020 scenario.

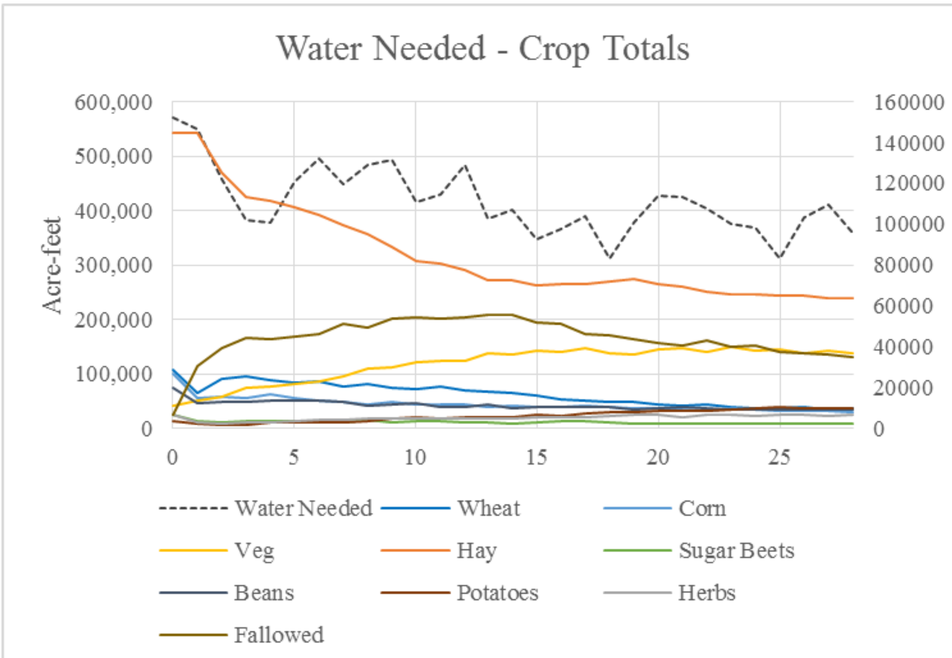


Figure 68: 2080 median scenario estimated water needed and crop totals.

Figure 69 shows the computed cost of water and water needed for the 2020 and 2080 median scenarios. This water needed reflects the potential changes in the NIR and crop and land use changes. The 2080 scenario consistently shows a higher cost of water than the 2020 scenario, which is due to the increase in NIR required by each crop and reductions of water available. Note that both scenarios show similar water needs over time even though there are increases in crop water NIR. This is likely due to the higher cost of water in the 2080 scenario causing more crops to convert to lower water need crops.

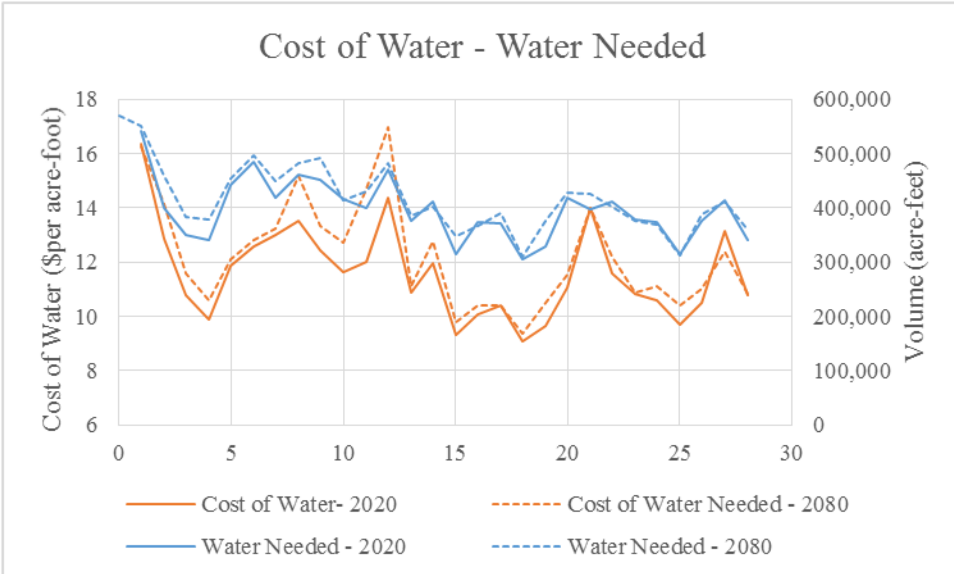


Figure 69: 2020 (solid) and 2080 (dashed) computed cost of water and water needed.

CHAPTER 6: DISCUSSION

The developed model utilized an agent based framework to assess trends in future water needs. This approach builds upon previous work, but uses new techniques for determining how crops will be selected, and therefore how much water will be needed. The concept of using future evapotranspiration or net irrigation water requirement values to determine the need for water is not new. However, using an agent based model to predict what crops individual farmers will grow in a probabilistic manner is unique.

Agent based models are best used to simulate systems where individual decisions drive outcomes. Farmers choosing crops and therefore determining water needs is a complex decision making process that does not conform to simple statistical relationships. In addition, the decision making process cannot be simulated by optimizing strategies or traditional modeling techniques because the Farmers do not optimize their decision and their decisions are not repeatable on an annual basis. Using the probabilities that support the individual decisions of the Farmer agent is the most representative technique for simulating the decision making process.

The probabilities that are used to drive the model show the likelihood that a piece of land growing a particular crop would change. Since these probabilities are estimated using actual acres of changes in crop acreages from field collected data, they reflect all of the decisions that were made by the valley farmers to determine what crops to grow.

In any given year, a farmer will use knowledge of past experiences and ideas about the future to choose what crops to grow. For example, one year, the farmer may decide to grow potatoes because potato prices have been increasing over the past few years. The next year, the farmer may change from potatoes to wheat because the water forecast is low and wheat requires less water to produce reasonable yields. From year to year, the factors contributing to the farmer's decision making process changes and therefore cannot be correlated annually. However, the aggregate of these decision is embedded in the probabilities that a farmer will change crops from one year to another, and this behavior can be simulated using an agent based framework.

By using the probabilities to determine how crops will be chosen, it removes the need for explicit variables and large quantities of data to analyze what might be grown in the future. This study used the relationship of potential revenue to the cost to grow a crop along with the cost of water to inform future decision. From the sensitivity analysis, it appears that this is a reasonable approach since the amount of water needed changed in ways that were expected.

The idea for this type of model was initiated by the WWCRA study that assessed West-Wide future agricultural water needs (Reclamation, 2014b). This study used static crop mixes for HUC-8 basins to determine the rate of water needed under varying future conditions. Given land use and potential crop changes under climate change, it was thought that those results may change if the crop mix changed.

The historical water required was compared to the water required calculated using a static crop mix from 2010. The static crop method underestimated the amount of NIR by up to 0.03 acre-feet per acre. This is within the error of the agent based model, so it could be argued that the static crop method is reasonable given the uncertainty in a more complex method. However, the static crop method results can be misleading when trying to determine the quantity of water that could be needed under future conditions, since most of the results indicate an increase the rate of water needed, which could be interpreted as an increase in the total volumetric need for water.

When comparing the rates calculated using the static crop mix as in the WWCRA study versus what was calculated using the method developed in this study, the rate of water needed tends to be overestimated by as much as 0.17 acre-feet per acre (Figure 70). This is because the static crop method does not allow for a reduction in higher water need crops as conditions change, which reflects the need for a more complex method.

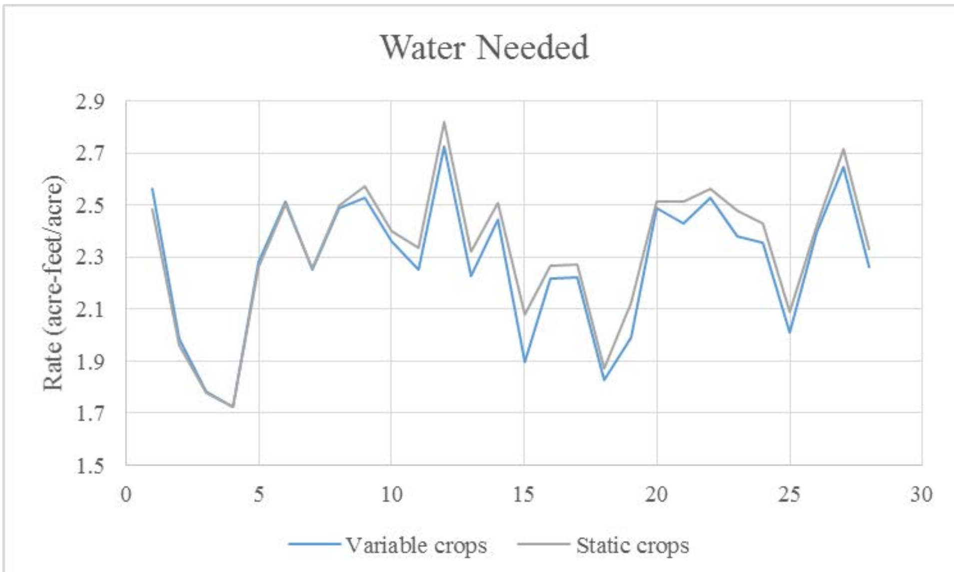


Figure 70: Rate of water needed calculated using variable crops and static crops.

Figure 71 shows the rate of water needed calculated by dividing the amount of water needed by the acres of crops grown with the variable crops. The figure also shows the total volume of water needed. Note that the volume of water needed decreases over time, but the rate does not.

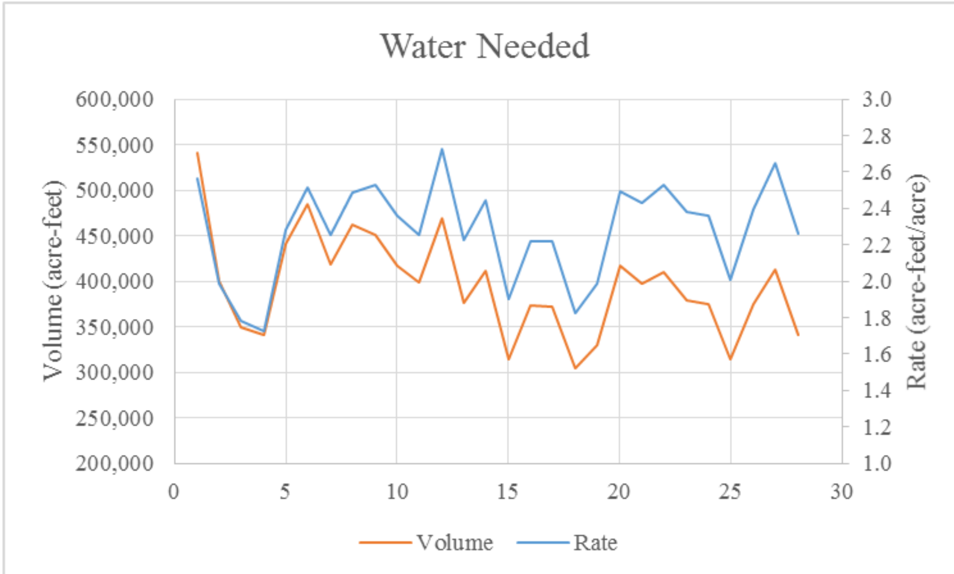


Figure 71: Water needed shown as a volume and rate.

The importance of this should not be minimized since the results of these study types are often used to make general statements about the potential future need for water. By showing the results as a rate, one could reasonably assume that there may be a constant or increased need of water under future conditions. However, Figure 72 indicates that although the rate of water increases in the 2080 scenario, the total volume of water needed decreases.

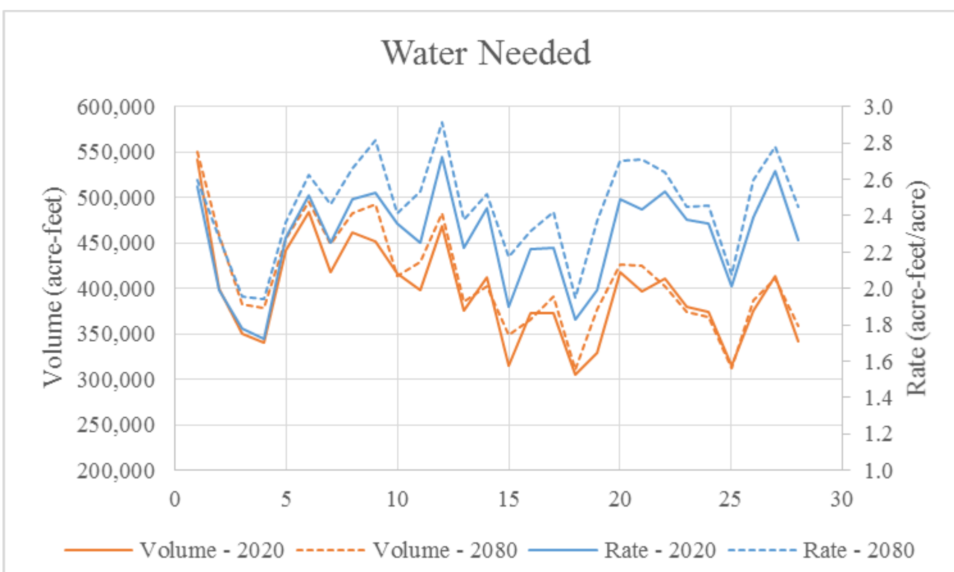


Figure 72: Water needed shown as a volume and rate for 2020 and 2080 scenarios.

The developed model focused on the computing amount of water needed to grow crops and did not consider the amount of water necessary to transport that water to the crops. In many regulated river basins in the Western U.S., conveyance loss and on-farm loss make up a substantial portion of water that is diverted from the river. Although this study showed a potential decrease in the need for water, water rights will still allow the same amount of water to be diverted from the river, if they are maintained. So, although the need for water decreases, the amount of total water diverted from the river may not decrease over time. This could lead to increased groundwater recharge as water flows through canals and is applied to lands. It could also result in larger quantities of water being returned to the river via bypass canals and a potential increase in carryover reservoir storage. An alternate possibility is that the new land use type could require less water resulting in less water being diverted from the river and therefore less groundwater recharge.

If a decrease in water need could be relied upon by water right holders, they may be inclined to transfer a portion of their water right to other users, though the priority date will change with that transfer. In addition, storage contract holders may be willing to rent or sell portions of their storage. Convincing water right holders that they will not need their water in the future is not an easy task and will likely take years of experiences, rather than models or scientific speculation, to cause a change.

Model Limitations and Future Areas of Study

The developed model provides reasonable estimates of the amount of water needed to irrigate crops in a basin. As the size of the area of interest decreases, the accuracy of the model decreases as was seen in the Phyllis District. This is likely due to the number of Farms making decisions about the types of crops that are grown, in that a single Farm can have more influence on the number of acres of a single crop when there are fewer Farms. Agent based models, in general, are better used to estimate the behavior of the aggregate of agents, not the behavior of a single agent, which is what was seen in this model.

The model assumes that each Farm will receive its total request of water in any given year. This is supported by the actual operation in the Boise River Valley, where it is rare that there is a water shortage. When there is a shortage of surface water or a limitation based on water rights, there are a number of other sources available to the Farm to make up the difference including renting water and supplementing with groundwater. The Farm will likely pay more for the water, however, which is accounted for in the model. This assumption would not be valid in the case where water supplies in the basin decrease to the point where supplemental sources are no longer available. In that case, the price received for the crops could be adjusted to account for decreased crop yields that would occur under water shortages.

The model assumes that lands converted to developed lands will no longer receive irrigation water. However, portions of Farms can convert to developed lands while others remain irrigated. This is meant to account for some lands that may be converted to developed lands but still receive irrigation water, as can sometimes happen in the Boise Valley. Lands categorized as developed are considered fully developed since the CDL pixels account for irrigated lawns. This assumption could results in a lower estimate of irrigation water needed if portions of developed lands still receive irrigation water.

The model combines the cost of surface water into a single value when differing sources of surface water (natural flow versus stored water) can cost different prices. Since the model is sensitive to the cost of surface water, more refinement in this cost may add more accuracy to the model. The model also assumes that the price received and cost to grow individual crops are static through the model runs. Adding functionality that would adjust the price received and cost to grow may impact the accuracy of the model and also change the results, given that the model is sensitive to the crop change factors.

The model assumes that all of the crops will rotate every year except for hay and herbs. It is possible that other crop types may not rotate every year. Additional functionality could be added to account for multiple year changes in crop type.

In order to transfer this model to other basins, it would be important to add functionality that would account for limitations in water by adjusting the price received by a decrease in yield. In addition, to account for changing conditions in water availability, it would be important to add a dynamic component to the cost of groundwater and drain water value. In this model, the cost of groundwater is based on a depth of 20 feet; however, a groundwater model could inform the developed model with spatially and time varying depths that could better account for the cost of groundwater under changing conditions. The same is true for drain water; a groundwater model could inform the volume of drain water available in a year given groundwater elevations.

Lastly, additional functionality could be added that takes further advantage of the agent based modeling platform. The current model uses the functions that allow for individual decisions being made based on individual experiences. However, additional functionality could be added to account for the interactions between farmers, between farmers and other land owners, and between farmers and municipalities. These features could allow for a more complete picture of water needs in a basin.

CHAPTER 7: CONCLUSION

The intent of this study was to develop an agent based model that could estimate the amount of water needed for agricultural purposes. An agent based model was developed that represented District, Farm, and Crop Agents in a regulated river system. The agents interact to determine the types of crops grown by each Farm to compute the amount of agricultural water needed for the basin.

Each Farm has a crop change probability table that represents the likelihood that the Farm will change a field growing one crop type to another each year. The table incorporates the Farm's historical behaviors, individual knowledge to grow particular crops, and available equipment. The table is adjusted after each year to account for new experiences driven by the availability of water, the amount of water required to successfully grow the chosen crops, and the cost of the varying sources of water.

The agent based model developed was able to estimate the amount of water needed by the basin with nine percent of the historical water needed. It was less accurate when focused on individual basins. It was reasonable at estimating individual crop types that were grown throughout the basin, though it more closely simulated trends in acres grown rather than the year to year variability.

When simulating longer time periods, the model showed that the overall need for water decreased. This was partly due to a shift in to crops that require less water and have a higher profit potential, and partly due to an increase in lands being developed. This was true even for the future climate scenario that showed in increase in crop water needs due to higher temperatures.

The results of this study and the development of a model that could simulate future water needs show that agent based models can provide a framework that combines the many processes that inform farmer's decisions. Many of the other tools currently used and available to water managers do not account for all of these processes and may lead to incomplete estimates of future water need. This study showed the potential use of agent based models to inform future decisions and should be further explored.

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