Response to Reviewers

Referee #1

Water resources management is a comprehensive issue which integrates hydrology cycle and water use. Water scarcity is a pressing problem in the western U.S., and the management is fairly complex. A solid and easy-to-use modeling tool that incorporates water rights information within a hydrological model will definitely help with water management decision making. However, due to the complexity of simulating the water allocation based on prior appropriation water right doctrine, hydrologic modeling research often does not explicitly include water rights. The few examples include the Water Rights Analysis Package (WRAP) and VIC-Cropsys. The current study presented valuable attempts to simulate the water allocation based on water rights. The study is unique than others in that it not only considers evapotranspiration and soil moisture in agricultural land, but also considers the water availability simulated in the streams and maximum allowed water quote/seniority based on the water right regulations. As such, it is truly an integration of social and biophysical processes in a modeling framework, considering hydrology, agriculture, and irrigation based on water law. The authors tested their model in the Treasure Valley, Idaho, which is a typical western semi-arid region, and the model is proved to capture the spatial allocation and timing of irrigation water use quite well. The calibration and validation processes seem a bit simple considering the model parameters involved and the complexity of the model. It is, thought, solid. The model is potentially a great tool that is applicable to many places in the western U.S. facing similar water resources challenges and following Prior Appropriation Doctrine. The approach also has the potential to be extended to simulate other water uses (industrial, domestic, municipal, commercial water use etc.) as long as the same prior appropriation doctrine is used. The manuscript is well organized and easy to follow, and the topic is of interest to HESS readers. I would recommend publication of the work with minor revisions.

Response: We are very glad that the reviewer agrees with our contribution. We appreciate the reviewer nicely summarized the key aspects of our study and pointed out their importance. Below, we respond to the minor concerns from the reviewer in details.

The minor concerns are as follows.

1. The authors calibrated 9 parameters and left 5 parameters as constant. It should be justified how the 5 constant parameters are selected? Based on sensitivity analysis or literature?

   Response: The selection of parameters for calibration is based on a combination of literature review and data availability. The reasons can be summarized as follows:

   (1) HBV is not a new model itself, and has a rich literature to guide on parameter selection. It has been widely tested that LP, CFR and CWH are not sensitive to model performance [Sælthun, 1996; Lawrence et al., 2009, and so on]. We have included another reference in the revision (Line 367).

   (2) FC and WP values are readily available data for the region. The watershed is quite small and has relatively uniform soil characteristics in agricultural regions, which can be reflected from the NRCS data sources. We have included the citation link of the values in the revision.

2. Figure 5 caption does not match with the content of the figure.

Response: Thank you for the sharp catch. We revised the figure to remove cumulative values which made the daily comparison less clear. We also changed the title in the revision.

3. Table 1 should list the temporal and/or spatial resolution of the data used in the study.

   Response: Thank you for the suggestion. We have revised the table slightly to include temporal and/or spatial resolution for all the datasets that are applicable.

4. For hydrologic modeling, the longer period of records is always better. However, to model water use, dry years play much bigger role as it is the time competing users need harvest water from hydrologic system simultaneously. The model is calibrated (verified) using 2006 to 2013. Please add short description of the period of records. It is dry or wet when much longer periods are consider? From the figures, one can only see that high flow vary significantly but low flow seems stable over the period.

   Response: Thank you for the suggestion. This is a very critical point. The reviewer is definitely correct that longer calibration and validation period will be better.

   The water use in the Treasure Valley is quite unique in that the water released from the upstream reservoir controls the water amount for downstream users as shown in the hydrograph. From the hydrograph, one can easily see a similar water use pattern every year starting from late spring. The reason is that the upstream reservoir is used for both flood control and irrigation, and has limited storage. If the snow accumulation is high, in early spring, water needs to be released to make sure that downstream city is safe, which reflects the high discharge in the "wet" years. From 2006 to 2013, we have typical wet years (2006, 2008, 2011, 2012) and dry years (2007 and 2013) included, and the relatively shorter periods saves a lot of computational time. So, we used the periods of 2006 ~ 2013 for calibration and validation purposes.

   We added some sentences describing the reasons for the selection of the period of records (Line 361 - 364).

5. From water resources management perspective, decision making often prefers conservative estimates. If a model is meant to be used to manage water during drought, underestimation of water availability is often preferred than overestimation. I am glad that the authors acknowledged that the limitation of overestimation and provided insights on possible reasons.

   Response: Thank you for the comment.

Response to Anonymous Referee #2

Han and colleagues address the important challenge of agricultural water management in a region prone to water stress. They develop a spatially explicit model of the Treasure Valley area in Idaho, U.S. that couples biophysical processes and water rights. Specifically, this model aims to diagnose the times and places where water supplies are insufficient to meet agricultural demands by incorporating the quantity and seniority of water rights from the Boise River. Irrigation water significantly alters the water balance and its application is determined not just by hydrological availability but the laws governing water rights. The integration of water rights in a spatially explicit model has the potential to lead to new insights on the challenges of water management and the opportunities for improvement. The manuscript is well written and the topic is of interest to Hydrology and Earth Systems Science readers. However, I do have a series of minor comments that would strengthen the paper. I recommend publication after minor revisions.

Response: We appreciate the reviewer's summarization of our research, and the encouragement on publication. We are addressing the reviewer's comments below in details, and will have all of them included in our revision.

1) The terms defined starting on line 315 would be clearer in a numbered or bulleted list.

Response: We used bullet list in the revision (Line 318 - 326).

2) On line 339 'simulates' should read 'simulating.'

Response: We changed the word in the revision (Line 342).

3) The Nash-Sutcliffe Efficiency Coefficient is referred to as both the 'Nash-Sutcliffe Coefficient' (line 352) and the 'Nash-Sutcliffe Efficiency' (line 366) and abbreviated as both 'NS' (line 399) and 'E' (line 366). Please revise for consistency.

Response: Thank you for catching the inconsistencies. We now consistently use 'Nash-Sutcliffe Coefficient' and abbreviate it as 'E' in the revision.

4) In Figure 4, label the two panels a and b or similar for clarity

Response: Thank you for the suggestion. We have labeled the panels as suggested.

5) In the model, the reservoir operations pass through natural flows within target range. However, fall flows at the Parma Station are consistently under predicted. Please discuss the potential causes of this discrepancy.

Response: We appreciate the reviewer bringing up the point. We realized this issue and discussed about it in lines 386 – 393 and lines 527 - 537. The major reasons are: 1) The model groundwater supply is assumed to be unlimited for the current situation. This reflects the truth of the current situation and simplifies the model, but will lead to unbalance of water budget; 2) The water pumped out of the watershed has not been considered in the current study. This is a relatively small portion of water use, but will specifically affect the discharge at Parma River station. The water management has to deal with the conflicts between political boundaries and watershed boundaries, and that is one of the directions for further work. We have discussed this issue in Lines 562-569 in the revision.

6) Figure 5 is hard to read in black and white. Making this figure consistent with Figure 4 would resolve the issue.

Response: We apologize for placing the wrong caption for the figure, and have corrected it in the revision. We also changed the line style to make it more readable in black and white.

7) Figures 7 and 8 offer a useful visual to compare the spatial allocation of water based on water rights and the modeled spatial allocation of water. However, the different units (feet vs. mm) make this comparison misleading. Please revise using consistent units, color scheme, and scale.

Response: Thank you for the suggestion. We consistently use the SI units in the revision. The values in the specific figure has been normalized to 0~1, so it is unitless.

8) In Figures 8 and 11 the domain is circled not outlined as noted in the caption. Please revise for clarity.

Response: We have had the domain circled in the figure. We are now using thicker lines to make the boundary clearer.

9) On line 455 note the average surface and groundwater usage in the model and Figure 10 shows the average unsatisfied surface water per month. Is there any available data to compare these results to? Are summer water shortages reported by local farmers?

Response: Unfortunately, there are no quantified numbers to compare to. The summer shortages have been reported by local farmers through our stakeholder conversations, and that is a big concern for local farmers right now. But so far, we do not have quantified data for that.

10) How does Figure 9 support the claim that allocated water is a complex nonlinear issue (line 553)?

Response: We reworded the sentence to make it clear. We meant to remind readers that the water allocation and water scarcity in a certain year is not linearly related to the current year precipitation amount. Figure 9 can demonstrate that water allocation is high in the dry year 2007 as irrigation water can be received from the snow fall from the previous year (Line 556 - 560).

11) On line 566 ‘corporation’ should read ‘cooperation.’

Response: Thank you. We changed it.

12) This model assumes all farmers make irrigation decisions rationally based on water availability. However, the heterogeneity of decision making may have important implications here (see Noel and Cai 2017). I understand that an analysis of this is out of the scope of the current work, but speaking to the implications of rational decision making as a simplifying assumption would augment the discussion section.

Response: Thank you. We added discussions on the complexity of decision making (Line 591 - 595).

Response to Anonymous Referee #3

The paper "Coupling biophysical processes and water rights to simulate spatially distributed water use in an intensively managed hydrologic system" by Han et al. presents a modelling framework to integrate water rights allocation into a hydrologic model capture the spatial distribution of irrigation water diversion in semi-arid basins in Western US. Agricultural irrigation is the largest water consumption, but the socioeconomic and institutional factors affecting irrigation behavior are generally not well represented in hydrologic models. This paper provides an effort to better representing anthropogenic factors in biophysical models and will provide insights on how better water use regulation will support sustainability of water resources management. The paper is well written and the results are clearly presented. I would suggest a minor revision to the manuscript. Below are some specific comments:

Response: We appreciate the positive feedback from the reviewer, and are very happy to respond to the specific questions below.

In Line 292, how is water diversion water loss handled in the model? Is diversion water loss added to soil or groundwater or river near the diversion channel? Speaking of irrigation return flow, will the water loss be considered as return flow? Due to the significant amount of water loss (60% of diverted water), more details are needed. This would also provide important information about how irrigation efficiency will affect water allocation and stream flow.

Response: Water loss is a very complex issue related to seepage along the canals, evapotranspiration, direct flow back to streams etc. The model has no way to capture those details, nor do we have observational data to support the simulation of those water loss details. As such, we took a simple approach by assigning a lump-sum coefficient to reflect the whole water loss. The "lost" water is still applied to the irrigation land, so that it can either evaporates or infiltrates. Part of the infiltrated water will be routed to the stream based on the HBV model. In this way, we are able to capture the diversion rate from the stream correctly. As such, the actual spatial allocation rate in the farm land will be in a smaller scale than the simulation result as part of the water is lost along the canals before arriving at the farmlands. We added a sentence to inform readers about this (Line 292 -294).

In Line 190, the land use and land cover in 2011 is used for the whole simulation. Does the irrigated crop area vary significantly during the simulation period?

Response: Thank you for pointing out this important issue. For this study, we temporarily used the 2011 land use data for the whole simulation. There is certainly land use change over the years, but for the 8-year simulation period, the change is not significant. Our next step is to project the future water use until 2100, and land use change will be a key factor to consider in the long run.

In Line 294 - Line 306, the irrigation requirements are satisfied based on the seniority of water rights. It would be interesting to see the model results on the allocated or unsatisfied water from different water rights seniority groups. For example, how much water is demanded and actually diverted for different water rights seniority groups? Will senior and junior water rights holders will be affected in wet/dry years? Since the model is unique in representing the water rights, how water is actually diverted to different water right seniority groups would provide important information for water resources management.

Response: Thank you. We totally agree. The water rights that are shut off or suspended are very important factors to inform stakeholders. In the current work, we are not able to fully capture those information, but we are trying to have more parameters summarized in our future work.

The unit of y axis in Figure 5 is misleading. The blue color is for discharge rate (mˆ3/s), while the red line is discharge volume (mˆ3). Is it possible to represent the simulated and observed irrigation water in a same unit?

Response: We apologize for this mistake. The other reviewers also have pointed out this issue. We have addressed it in the revision.

The black dash line of Black Canyon Irrigation District in Figure 8 is difficult to capture. In addition, the average annual allocated irrigation water is some places are more than 1000 mm/yr, or even more than 1500 mm/yr. It seems to me the irrigation amount is quite big. Will farmers in these regions apply some much water in the fields?

Response: Thank you. We changed the way how the Black Canyon Irrigation District is reflected in the revision by making thicker lines of the boundary.
With regard to the allocation amount, the number is higher than actual value. The reason is that part of the “loss” water is applied to the farmland. This problem has been answered earlier above.

Farmers’ irrigation behaviors are affected by many factors, such as irrigation technology, insurance, farmer’s preference on profit/risk. Although these are beyond the scope of this study, the authors should briefly discuss it and cite some existing literature on how farmers’ behavior affect the hydrologic systems.

Response: Thank you. We added some discussions on the complexity of farmer’s decision making in the revision (Line 591 -595).

Coupling biophysical processes and water rights to simulate spatially distributed water use in an intensively managed hydrologic system

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Abstract: Humans have significantly altered the redistribution of water in intensively managed hydrologic systems, shifting the spatiotemporal patterns of surface water. Evaluating water availability requires integration of hydrologic processes and associated human influences. In this study, we summarize the development and evaluation of an extensible hydrologic model that explicitly integrates water rights to spatially distribute irrigation waters in a semi-arid agricultural region in the Western United States, using the Envision integrated modeling platform. The model captures both human and biophysical systems, particularly the diversion of water from the Boise River, which is the main water source that supports irrigated agriculture in this region. In agricultural areas, water demand is estimated as a function of crop type and local environmental conditions. Surface water to meet crop demand is diverted from the stream reaches, constrained by the amount of water available in the stream, the water rights-appropriated amount and the priority dates associated with particular places of use. Results, measured by flow rates at gaged stream and canal locations within the study area, suggest that the impacts of irrigation activities on the magnitude and timing of flows through this intensively managed system are well captured. The multi-year averaged diverted water from the Boise River matches observations well, reflecting the appropriation of water according to the water rights database. Because of the spatially explicit implementation of surface water diversion. The model can help diagnose places and times that water resources is likely insufficient to meet agricultural water demands, and inform future water management decisions.

Highlights:

- A novel tool that explicitly integrates water rights to spatially allocate irrigation
- Captures elements of both human and biophysical systems
- Inform future water management policies and decisions

Keywords: Integrated modeling; Treasure Valley; Irrigation; HBV; Water use; Water right

1 Introduction

1.1 Background

Increasing water demands for both agricultural and domestic consumption under the stress of climate change and increasing population represents a global environmental challenge [*Vörösmarty et al.*, 2000]. This increasingly limited hydrologic supply exists within the context of often extensive built hydrologic infrastructure. In turn, the management of that infrastructure is driven by complex social processes and decision making [*Pahl-Wostl*, 2007]. Accordingly, projecting how climate change and human activities will alter water availability in the future requires developing models that can integrate human decision making and biophysical processes [*Girard et al.*, 2015]. This challenge is particularly acute in arid and semi-arid regions where water resources are typically limited and actively managed to support irrigation-supported agriculture [*Falkenmark*, 2013].

Explicit integration of both human and environmental processes in hydrologic modeling is an area of active investigation and a variety of approaches are being used. For example, *Jakeman and Letcher* [2003] introduced attempts in Australia to integrate between hydrological and economic models using a nodal network approach. *Ahrends et al.* [2008] developed a coupled model system, consisting of a distributed hydrological model and an economic optimization model, communicating via model interfaces, to investigate regional interdependencies between irrigated agriculture and regional water balance in West Africa. *Ferguson and Maxwell* [2012] applied an integrated hydrologic model to compare effects of climate change and water management on terrestrial water and energy budgets of a representative agricultural watershed in the semi-arid Southern Great Plains of the United States. *Willaarts et al.* [2012] discussed win-win management solutions through societal evaluation of hydrological ecosystem services. *Cai et al.* [2013] evaluated potential hydrologic alterations of the Yangtze River under four scenarios of reservoir operation strategies by balancing human and environmental factors. *Kirby et al.* [2013] conducted a basin-wide simulation of flows and diversions for economic and policy analysis in the Murray-Darling Basin. *Laniak et al.* [2013] summarized recent progress and difficulties of integrated environmental modeling and urged that global community of stakeholders transcend social, and organizational boundaries and pursue greater levels of collaboration.

In the arid and semi-arid regions agriculture often relies heavily on irrigation and is typically the largest water use [*Döll and Siebert*, 2002; *Shiklomanov*, 2000]. Irrigation diverts water to the originally dry lands, significantly altering the hydrological cycle. Because amount and timing of applied irrigation water is, ultimately, a local decision made by farmers for individual fields, it is particularly challenging to explicitly express these changes in a way that captures resulting spatially and temporally variable impacts.

A variety of approaches have been taken to express irrigation in hydrologic models. Many models rely on a simple soil-water balance module, and empirically estimate the agricultural water demand. For example, *Gisser and Mercado* [1972] applied empirically estimated agricultural water demand into a hydrologic model in Pecos Basi. *Döll and Siebert* [2002] developed a global irrigation model to calculate the irrigation water requirements depending actual and potential evapotranspiration rates. *Cai et al.* [2012] applied an irrigation diagnosis model to a regional irrigation system in the Yangtze River Basin to analyze the local water budget. These models are advantageous for hydrologic-economic assessment, but typically discount some details of the physical system. Physically based models can simulate processes influencing the water balance, including crop growth, irrigation, fertilizer applications and solute transport. Examples include the soil-water-atmosphere-plant (SWAP) model [*Dam et al.*, 1997; *Droogers et al.*, 2000], the Environmental Policy Integrated Climate (EPIC) model [*Gassman et al.*, 2005] and the CropSyst model [*Stöckle et al.*, 2003]. Generally, these models are operated as point-scale models and do not express processes in a spatially explicit manner. With expanded computational capacity and the progress of GIS, increasing interest has been put on the integration of agricultural based models with spatially-distributed hydrologic models, e.g., VIC-CropSyst [*Stöckle et al.*, 2014], GEPIC [*Liu et al.*, 2007]. Generally, the commonly used approach in irrigation modeling is to set soil moisture to field capacity or soil saturation or set a fixed evapotranspiration rate in irrigated areas [*Leng et al.*, 2014], which can lead to inaccurate water budget and an inability to represent irrigation in a more realistic way. It is also a common practice to assume unlimited water supply when considering the sources and availability of irrigation water, which does not reflect the truth in many water limited environments [*Sorooshian et al.*, 2012]. As such, we are aiming to incorporate irrigation activities in our model in a more realistic way.

In the western United States, water is mostly allocated according to legally defined water rights following the Prior Appropriation Doctrine, which basically defines that water rights are determined by priority of beneficial use; historical use of water creates a right to the water. This means that the irrigation amount is dependent not only on physically defined water availability, but also on constraints dictated by legally defined water rights. In these systems water use for irrigation is, therefore, the product of both environmental constraints (e.g. basin scale water availability and evaporative demand) and human constraints through water rights allocations. Accordingly, water rights represent an important, and well defined, constraint on irrigation water use in these systems. However, few models take consideration of the influence of water rights on the redistribution of water. The state of Texas has implemented a modeling system called Water Rights Analysis Package (WRAP) to assess water availability and reliability of water resources with local water rights [*Wurbs*, 2005a; b], but the model is not fully spatially distributed and the model functions on a monthly scale.

In this study, we demonstrate an approach that integrates water diversion for irrigation based on water rights within a physically-based model of hydrologic processes. We outline the development of the core elements of both the biophysical and social system components of the model that appear critical to represent the redistribution of water within the study area.

1.2 Study area

The Treasure Valley area, located in southwest Idaho, is the most populous region of Idaho and contains its three largest cities, Boise, Nampa and Meridian (Figure 1), but is also home to an extensive irrigation-supported agriculture. The area collectively comprises about 40% of state's total population, with an area of 3323 km^2. Farm land occupies about 40% of the total landscape, with an area of 1289 km^2, and relies heavily on irrigation through about 1700 km of constructed canals.

Climate is generally semi-arid Mediterranean pattern with a hot dry summer and cold wet winter, with strong spatial and temporal fluctuations in temperature and rainfall. Annual rainfall varies substantially within the basin from ~ 700 mm in the northeast foothills to ~ 200 mm in the southwest at the Lake Lowell, with a historical average of about 296 mm/yr at Boise Air Terminal weather station. About 50% of the total precipitation occurs during the non-irrigation season. Like many intensively managed landscapes in semiarid and mountainous regions of the world, a series of reservoirs upstream of the Treasure Valley regulate and homogenize flows out of the upper basin into the Boise River. The lower-most of these reservoirs, Lucky Peak, is operated jointly by the US Army Corps of Engineers and the Bureau of Reclamation for purposes of flood control and irrigation water supply. From Lucky Peak Reservoir, the Boise River exits the mountains and flows about 103 km (64 miles) northwestward through the Treasure Valley to its confluence with the Snake River. The Treasure Valley is bounded to the north by the Boise foothills and to the south by the Snake River. A number of canals and diversion dams have been built along the Boise River water course to allocate water resources.

Among the largest of these canals is the New York Canal that diverts water directly from the Boise River about 1.6 km downstream of the Lucky Peak dam. During non-irrigation season, the New York Canal carries a portion of the water to fill Lake Lowell, a reservoir within the Treasure Valley area, for use during the irrigation season. During irrigation season, the New York Canal carries a significant portion of the water from the Boise River and diverts it into distributary canals within the agricultural areas of the Treasure Valley. With the benefit of irrigation, population in the Treasure Valley has been growing rapidly and consistently since the 1870s. Urban growth and increasing irrigation activities drive land use change and reallocation of water resources. Despite the importance of water resources and potential threats of water scarcity, there have been limited integrative studies regarding water availability and scarcity in this area. The Idaho Department of Water Resources (IDWR) conducted the Treasure Valley Hydrologic Project starting in 1996, aiming to develop a better understanding of water resources in the Treasure Valley and to evaluate changes in regional and local groundwater conditions. Supported by this project, *Petrich [2004b]* characterized and simulated groundwater flow in the Lower Boise River Basin, and analyzed the water budgets for the regional aquifer system based on 1996 and 2000 calendar-year inflow and outflow estimates [*Petrich*, 2004b; *Urban and Petrich*, 1996]. Local, state, cities and some federal agencies have also supported or conducted a few water demand studies that characterized the local land use and the associated domestic, commercial, municipal, and industrial water demands. However, most of these studies are conducted at the conceptual level by estimating total water budgets. *Xu et al.* [2014] conducted a hedonic analysis to estimate the response of agricultural land use to water supply information under the Prior Appropriation Doctrine. Their results are informative at the scale of the entire Treasure Valley but also lack spatiotemporally dynamic components that could be used to reveal particular locations in space and periods in time where water demand and supply are out of balance. This research seeks a practical integration of the spatiotemporal detail that is available in the water rights database with the local spatiotemporal dynamics of surface water hydrology. An important outcome of this study is an extensible modeling framework that can serve as a foundational tool to capture and evaluate the complex interactions between the social and biophysical systems related to water use in an integrated way.

Figure 1 Study Area: ~~the~~The Treasure Valley.

2 Methods

2.1 Envision platform and datasets

The model developed in this study is based on the Envision modeling tool, a spatially explicit integrated simulation platform that can be used to integrate elements of biophysical and social systems [*J P Bolte et al.*, 2007; *Inouye*, 2014]. Envision provides a geospatial software framework to coordinate the interoperation of component models used to represent essential processes and properties of the coupled social and biophysical systems being simulated. Envision has been used in a variety of projects, e.g., to develop alterative future scenarios under three growth management strategies for the Puget Sound Region in Washington, US [*J Bolte and Vache*, 2010], construct a land use / land cover (LULC) agent based modeling for the Motueka catchment, Australia [*Montes de Oca Munguia et al.*], evaluate potential impacts of climate change on vegetation cover in the Willametter River Basin, Oregon, US [*Turner et al.*, 2015], and understand coupled natural and human systems on fire prone landscapes [*Barros et al.,* 2015].

In Envision, the spatial domain is represented by a collection of polygons, called Integrated Decision Units (IDUs). Each IDU polygon is associated to important geospatial attributes characterizing both biophysical and social properties (e.g., elevation, soil type, land use, population density, disturbance history, water right code, irrigation decision etc.). The IDU forms the fundamental spatial unit for integrated decision-making in Envision. The process of creating the IDU computational domain is somewhat ad hoc and iterative, but is meant to balance the competing demands of fidelity to spatial heterogeneity and associated computational cost. The IDU computational domain was constructed through a process that initially converted raster-based LULC information into a polygon layer by grouping adjacent sets of pixels with similar land-use/land-cover classes into polygons. Small polygons derived from a single LULC pixel within a larger polygon of a different land-use/land-cover class (i.e., with an area of 900 m^2 or less) were identified and deleted. The final constructed computational domain for the Treasure Valley consists of 32,508 IDUs (polygons).

A variety of dataset is required to build the model (Table 1), among which, spatial heterogeneity in the model is mainly reflected by three spatially explicit datasets: land cover, elevation, and meteorological inputs. The land cover data is collected from the Nation Land Cover Dataset, using the data of 2011. The elevation data is collected from the National Elevation Dataset with a spatial resolution of 30 m. The climate dataset is a spatially and temporally complete, high-resolution (4-km) gridded dataset of surface meteorological variables created by bias-correcting daily and sub-daily mesoscale reanalysis and assimilated precipitation from the NLDAS-2 using monthly temperature, precipitation and humidity from Parameter-elevation Regressions on Independent Slopes Model [*Abatzoglou and Brown*, 2012]. The stream network is defined from the NHDPlus V2 dataset, which represents stream networks as node-based line coverages. Segments between nodes are considered to be stream reaches and each IDU is assigned a stream reach for the purposes of simulating hydrologic routing. Artificial channels such as irrigation canals and drains are explicitly represented. However, as discussed below, they are functionally captured using the WaterMaster module, which simulates the allocated water based on water rights.

Table 1 Datasets used in the model

2.2 Hydrologic processes

In this study, we employ the module called Flow with a slightly changed Hydrologiska Byråns Vattenbalansavdelning (HBV) [*Bergström and Singh*, 1995; *Woodsmith Richard D. et al.*, 2007] plugin to represent hydrologic processes. Human interventions include reservoir operations, and agricultural irrigation which is simulated by another Flow plugin called WaterMaster. The primary focus of the current paper is to develop a framework to incorporate human activities, mainly irrigation, at the watershed scale, and provide solid basis for future integrated scenario projections.

Within Envision, the HBV model is applied in a semi-distributed way to delineated Hydrologic Response Units (HRUs) within the study domain affording the use of spatially distributed datasets such as daily gridded meteorological inputs, land cover, and elevation information [*Inouye*, 2014]. Within the model, HRUs are delineated by aggregating adjacent IDUs that are associated with a common LULC and similar elevation, and 4456 HRUs are composed. Hydrologic processes are simulated at the HRU-level, with fluxes being distributed uniformly to the IDUs within the HRU.

Here, we briefly describe the slightly changed HBV model (Figure 2). A catchment in the model is conceptualized as a series of linked reservoirs and is divided into 6 layers in this study: snowpack, melt, irrigated soil, non-irrigated soil, upper groundwater and lower groundwater. Runoff from the HRUs from different layers is then routed to streams using linear outflow equations. The water balance equation in Flow (HBV) can be described as:

$$P - ET - Q = \frac{d}{dt}[SP + SM + UZ + LZ + lakes] \quad \text{Eq. 1}$$

where, P = precipitation; ET = evapotranspiration; Q = runoff; SP = snow storage; SM = soil moisture storage; UZ = upper groundwater storage; LZ = lower groundwater storage; $lakes$ = lake storage.

The model simulates daily discharge using daily rainfall, temperature, and potential evapotranspiration as inputs. Precipitation is simulated to be either snow or rain depending on whether the temperature is above or below a threshold temperature (TT). Rainfall and snowmelt are then divided into water either filling the conceptual soil layer or recharge into groundwater depending on the current soil moisture, field capacity (FC), and the parameter “Beta” (Eq. 2).

$$F = \left(\frac{Soil\ Water}{FC}\right)^{\beta} \quad \text{Eq. 2}$$

where, F is the fraction of rain or snow. Evapotranspiration (ET) is simulated using the FAO56 Penman-Monteith method as specified by the UN Food and Agriculture Organization (FAO) in paper number 56 [*Allen et al.*, 1998] and in [*Allen and Robison*, 2007]. Generally, a crop coefficient Kc is developed to simplify and standardize the calculation and estimation of crop water use, and is an integration of the effects of crop properties and soil properties. As plants grow and develop, Kc varies over time and the values are obtained from AgriMet Pacific Northwest Cooperative Agricultural Weather Network. The potential ET of a specific crop, ET_c, is then calculated as in Eq. 3:

$$ET_c = K_c * ET_r \quad \text{Eq. 3}$$

where, ET_r is the reference evapotranspiration rate, the evapotranspiration rate for a standardized vegetated surface corresponding to a living, agricultural crop (usually using full cover alfalfa). For simplicity at this framework building stage, we do not include detailed crop categories and crop rotation schedules. Rather, we use the crop coefficients of alfalfa for all agricultural land use in the region due to the fact that most of the agricultural land in the Treasure Valley is fully irrigated. Crop coefficients are assigned for non-agricultural lands based on crop categories with ~~a~~ similar physical characteristics as an approximation (Table 2). Detailed evapotranspiration calculation methods could be referred to [*Allen and Robison*, 2007]. Actual ET in the model is constrained by soil moisture at each HRU, as simulated in each daily time step. The soil box is subdivided into two layers/fractions, irrigated soil and non-irrigated soil, to help facilitate water to be irrigated and evaporated from the irrigation areas. The response function consisting of two or three linear outflow equations depending on whether or not recharge in the upper groundwater box (SUZ) is above a threshold value (UZL) then transforms excess water from the soil layer to runoff (Eq. 4, Eq. 5, and Eq. 6).

$$Q0=K0\cdot(SUZ-UZL) \qquad \text{Eq. 4}$$

$$Q1=K1\cdot SUZ \qquad \text{Eq. 5}$$

$$Q2=K2\cdot SLZ \qquad \text{Eq. 6}$$

where, SUZ is the recharge (water depth) at the upper groundwater zone that is simulated at each time step, UZL is a threshold value, SLZ is the recharge (water depth) at the lower groundwater zone that is simulated at each time step. If SUZ > = UZL, then the total water that is routed to runoff is the summation of Q0, Q1 and Q2. If SUZ < UZL, then the total water that is routed to runoff is the summation of Q1 and Q2.

Table 2 Crop categories used to approximate the land use categories in the ET calculation

Figure 2 Flowchart of the Flow module in Envision. Note the human activities influencing water availability. Water is distributed by the local water rights data (irrigation activities), and is also constrained by the reservoir operations.

2.3 Simulation of water rights

Irrigated water allocation is simulated via a module called Watermaster (Figure 3) that adheres to publicly available water rights data in Idaho in accordance with the Prior Appropriation Doctrine [*Hutchins*, 1977; *Xu et al.*, 2014]. In this study, surface water and groundwater irrigation activities are simulated based on the water rights data updated in 2012 by IDWR. Each water right is associated with four attributes that are of critical importance to this study: (1) the Place of Use (POU), (2) the Point of Diversion (POD), (3) the priority date, and (4) the appropriated diversion rate.

The POU data is used to identify IDUs in the study domain with surface water and/or ground water rights. For surface water rights, water is extracted from the stream reach closest to the POD associated with that water right. In most cases in the Treasure Valley, the PODs are located along irrigation canals not explicitly being simulated, and the PODs are assumed to be the point at which water is originally diverted from a natural watercourse (A majority originally diverted from the Boise River due to its seniority and largest diversion capacity) into the associated supply canal system. The priority date of each water right determines whether or not water can be diverted from the stream reach associated with the POD and applied to the IDUs within a POU as irrigation on a particular date during the simulation. On each day of the simulation, WaterMaster determines all water rights active on that date and, based on the allocation rates of those water rights, determines the maximum flow of water that may be diverted at each stream reach associated with one or more PODs. The irrigation water demand at the POU is computed as the potential evapotranspiration for the agricultural IDUs within each POU with a composite loss coefficient which is currently set based on an overall estimation of 60% water loss from the original diversion to ultimate crop use. The coefficient was roughly estimated based on a local study of irrigation management in 1999 and the proposed potential improvement in the study to reflect the current irrigation efficiency [*Huter et al.*, 1999]. To simplify the model, the amount of diverted water is applied to the place places of use for evaporation or infiltration, and the amount of usable water for crops considers the loss coefficient. The amount of water demanded for diversion at the stream reach is then computed as the sum of water demand for all POUs associated with a POD along that reach. If there is sufficient streamflow to satisfy demand, the amount of water diverted equals the total demand. If there is insufficient streamflow in the reach to satisfy demand, then water rights must be curtailed. Water rights with highest seniority (i.e., earliest priority date) are satisfied and streamflow reduced by the allocation rate associated with that right, followed by the next most senior water right, and so forth until there is insufficient streamflow to meet demands of water right. At this point, that water right and all more junior rights are curtailed only for the current date and will resume water use whenever there is abundant stream flow later of the year. This approach simulates the effect of canals and distributaries without explicitly simulating the hydraulics of canal flow. Specifically, water is diverted from an actual place of diversion as captured by the IDWR database and applied to a place of use in accordance with the water rights database. For ground water rights, we assume unlimited groundwater source as of now due to the fact that groundwater resources are abundant for the withdrawal rates in the Treasure Valley [*Petrich*, 2004a]. On the valley-wide basis, the volume of ground water pumped during the year accounts only 15 to 20% of the total ground water recharge [*Urban and Petrich*, 1996]. Groundwater in the Treasure Valley is mainly recharged from the seepages from the canal system, flood irrigation and precipitation. Use of groundwater for irrigation is common, although surface water rights comprise a much larger proportion of agricultural water use on a volume basis in the Treasure Valley.

Here we would like to define a couple important terms used below:

- The allocated water indicates the amount of water that is met and diverted to the corresponding place of use in the model.
- The unsatisfied water indicates the amount of water that is not met for the corresponding place of use in the model.
- The appropriated diversion rate is calculated based only on the POD rates and the corresponding POUs, and reflects the amount of water that is potentially usable based on the existing water right maximum rates while ignores priority dates and physical constraints. It is calculated upon the water right dataset instead of being simulated by the model.

Figure 3 WaterMaster loop that makes use of the local water rights data for irrigation

2.4 Reservoirs and boundary condition

Reservoirs are considered part of the stream network in Envision. The location and physical constraints of the Lucky Peak Reservoir and Lake Lowell's dams are set up based on the data collected from the Hydromet database (Table 1). The Lucky Peak Reservoir receives water drained from the watersheds upstream of Boise River, and is the main water resources for the Treasure Valley. The historical inflows to the Lucky Peak Reservoir are used as inflow boundary condition for the model. Lake Lowell is an offstream reservoir formed by three earthfill dams enclosing a natural depression at southwest Treasure Valley. The reservoir naturally drains water and is also filled during the non-irrigation season by diversions at the Boise River Diversion Dam through New York Canal. In this study, we simplify the reservoir operations by setting the maximum and minimum flows at a downstream control point of each reservoir (Boise River at Diversion Dam for Lucky Peak Reservoir and Boise River near Parma River for Lake Lowell) based on historical daily extreme values to regulate the extreme flow released from the reservoirs. This setup is efficient while still simulatinges the normal operation of the Boise Project Board of Control. The operation basically aims to control flood in the Boise River for the safety of the city, uses the natural river flows until the Boise River falls to a certain level, and then switches to water stored in reservoirs and provides users a certain allotment of water they can use for the irrigation season. As such, by setting up maximum and minimum daily flows, the reservoirs are designed to release water in the dry seasons and control flooding water in the snow melt season of the area.

2.5 Model calibration and validation methods

The reliability of many hydrological models is dependent on calibration, which is the process of finding an optimal set of parameters that enable the model to closely match the behavior of the real system it represents [*Gupta et al.*, 1998]. We calibrated the model based on the Nash-Sutcliffe coefficient (Eq. 7) between the observed and simulated stream flows at two USGS gages – Boise River at Glenwood and Boise River near Parma, Idaho.

The Nash-Sutcliffe coefficient is calculated as:

$$E = 1 - \frac{\sum_{t=1}^{T}(Q_{obs}^{t} - Q_{sim}^{t})^2}{\sum_{t=1}^{T}(Q_{obs}^{t} - \overline{Q_{obs}})^2} \qquad \text{Eq. 7}$$

where, Q_{obs} is the observed discharge; Q_{sim} is the simulated discharge, and t is the time step at calculation, $\overline{Q_{obs}}$ is the mean observed discharge over the entire run. Nash-Sutcliffe coefficient can range from - ∞ to 1 (perfect match). An efficiency of negative value indicates that the mean value of the historical observations would be a better predictor than the hydrologic model. Most parameters used in the model are estimated using a Monte Carlo approach. The data from years of 2006 - 2009 are used for calibration processes, and from 2010 - 2013 are used for validation purpose. The time period is relatively short, however, contains typical wet years (2006, 2008, 2011, 2012) and dry years (2007, 2013). For each run, each parameter value was randomly selected from a uniform distribution; the minimum and maximum values of these distributions, listed in table 3, are generally adopted from *Sælthun* [1996], *Lawrence et al.* [2009], ~~and~~ *Abebe et al.* [2010], and *Inouye et al.* [2014]~~{Inouye, 2014 #23}~~. We simultaneously vary the values of the parameters within their target ranges, and run the model 1000 times. Then the best-fit parameter sets are selected through an assessment of the fit of simulated to observed runoff data based on visual inspection of fit and Nash-Sutcliffe coefficient (E) between the observed discharge and the simulated discharge. The parameters are conceptually based on physical parameters of the system. Although they are actually effective parameters that fit the model through calibration and do not necessarily represent actual physical properties, it would be beneficial to get physically representative values whenever possible. In this calibration process, we calibrate 9 parameters of the total 14 parameters, while setting 5 parameters constant to save computational time. The FC and WP values were adopted from the SSURGO dataset from the Natural Resources Conservation Service [www.ctgpc.com.cn].

Since LP, CFR and CWH are not sensitive to model performance [Seibert, 1997], a reasonable LP value was set based on local soil conditions, and CFR and CWH were held constant.

Table 3 Parameters used, the range considered for calibration and the calibrated values

3 Results

In this section, the calibration and validation results of the hydrological module are presented, the water right dataset is summarized, and the irrigation water use and water scarcity from 2006 – 2013 are analyzed.

3.1 Calibration and validation

The model was calibrated and validated against historical observations through discharge at two USGS gaging stations (Boise River at Glenwood and Boise River near Parma) and at the New York Canal. These two calibration targets reflect influences of different processes. The upper gaging station (Glenwood) is just down-stream from the New York Canal, the primary point of extraction but is up-stream of the majority of return flow to the Boise River, which is primarily in the lower portion of the river. In contrast, the Parma gaging station is located just above the confluence with the Snake River and is downstream of both the majority of the extraction and return flows. Accordingly, model results that successfully match the Glenwood gage provide a good indication of the model's capacity to simulate water consumption and associated removal, while comparing the model results to the Parma gage is more strongly influenced by the model's capacity to capture return flow.

A plot of the simulated and the observed flows at these two USGS sites for the calibration period (2006 – 2009) and the validation period (2010 – 2013) is shown in Figure 4. The model effectively captures the major high and low flow events, the extreme values of which are constrained by the downstream control points. For example, at Glenwood, the annual discharge is clearly dominated by three periods associated with late winter or spring high flows, irrigation season flows, and fall-winter low flows. The ~~NS~~ coefficient E, which is a criterion to estimate the goodness of fit between observational data and simulated data, is 0.82 during the calibration period and 0.67 during the validation period at the Glenwood site, and 0.69 during the calibration period and 0.62 during the validation period at the Parma site. The good fit to the Parma gage suggests the model captures return flow particularly well. We also compare the amount of water diverted to the New York Canal with the simulated results, and find a good match with a correlation coefficient of 0.92 (Figure 5), indicating that the model does a good job of capturing the diversion amount from the Boise River.

Figure 4 Simulated discharge and the observations during the calibration (2006 ~ 2009) and validation periods (2010 ~ 2013) at the Glenwood Station of Boise River (~~Upper~~ Panel a) and Parma Station of Boise River (~~Lower~~ Panel b).

Figure 5 Simulated irrigation amount and the observations averaged over the years of 2006 ~ 2013 at the New York Canal. The solid line~~Blue color lines~~ shows the observed ~~are~~ daily discharge rate in m^3/s, and the dashed ~~red color~~ line~~s~~ ~~are~~ shows the ~~cumulative~~ simulated discharge in m^3/s.

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3.2 A summary of the irrigation water rights

In the Treasure Valley, surface water is the main water source for irrigation, despite many more POD's for groundwater. Currently, there are 22,217 PODs and 21,492 places of use (POUs) in the study area, among which, 4,838 PODs and 3,859 POUs are appropriated for the irrigation use (Figure 6). In the following analysis, all water rights are irrigation water rights unless stated otherwise. Within all water rights database, 78% of the PODs use groundwater as water source, and only 22% use surface water as water source. However, surface water is still the main water source with regard to the amount of irrigated water supply. Surface water PODs are mainly located along the Boise River, usually with a relatively higher maximum allowed diversion rate per POD (maximum 38.21 m^3/s), while groundwater PODs are dispersed all over the irrigated lands, usually with a relatively smaller maximum allowed diversion rate per POD (maximum 2.47 m^3/s). Among all the surface water PODs, most surface water is mainly diverted from the Diversion Dam which connects New York Canal with Boise River. Multiple PODs overlap at the Diversion Dam with highly senior water rights, diverting about half of the stream flow from main branch of Boise River during the irrigation season. The diverted water provides the water resources for Lake Lowell and numerous irrigation canals downstream.

Figure 6 The spatial distribution of the Points of Diversion (PODs) for irrigation purpose, and the maximum allowed diversion rates.

3.3 Model simulated spatial and temporal distribution of water use

Comparing simulated water use with that predicted based on appropriated rates suggests the model does a good job of spatially distributing water use. The summarized appropriation rate generally matches the boundary of the irrigation districts (Figure 7). According to the normalized appropriation rate, most of the water should be appropriated to the southwest part of the Treasure Valley, e.g. Nampa-Meridian, and New York irrigation districts. In contrast, a relatively small amount of water should be appropriated to those areas along the Boise River and into the Black Canyon irrigation district which is located at the northwest part of the Treasure Valley.

Figure 7 The annual appropriated diversion rates normalized based on water rights maximum allowed diversion rates and place of use, indicating the relative spatial distribution of potential usable water. The irrigation district boundaries and the names of major irrigation districts are also shown. ~~The annual appropriated diversion rates calculated based on water rights maximum allowed diversion rates and place of use, indicating the potential usable water. The irrigation district boundaries and the names of major irrigation districts are also shown.~~

The model simulated allocation rate follows these spatial patterns of the appropriated rate (Figure 8). The southwest part of the study domain receives the most allocated water, while the northwest part and the downstream section of Boise River is allocated less water (Figure 8).

Figure 8 The spatial distribution of the annual allocated irrigation water averaged over the simulation period. The domain that is within the thick outline ~~circled~~ is Black Canyon Irrigation District, which receives additional irrigation water from outside of the domain, where the water allocation is underestimated.

The simulated water allocation confirms that surface water is the main water source with regard to the amount of allocated water, as shown by the model simulated annual and monthly allocated surface water rates, and allocated groundwater rates (Figure 9, Figure 10). The allocated surface water discharge rate is ~ 21.3 m^3/s averaged over 2006 to 2013, while the allocated groundwater is only ~ 4.0 m^3/s.

Figure 9: Average daily allocated surface water, groundwater and unsatisfied surface water use for each year.

Figure 10: Average daily allocated surface water, groundwater and unsatisfied surface water use for each month from 2006 to 2013.

The simulated water allocation also reflects the seasonal irrigation water use pattern. The irrigation season in the Treasure Valley occurs from April to November when precipitation is rare and temperature is high. As expected, most of the irrigation activities happens from May to October, representing over 95.6% of the annual total irrigation amount. The peak irrigation season is June, July and August, which irrigates 61.1% of the annual irrigation amount.

4 Discussions

4.1 The model's contribution to inform decision-making

4.1.1 The model reveals water scarcity and its causes by unsatisfied water distribution

The irrigation water scarcity is divided into 4 categories based on the annual unsatisfied irrigation water amount: Adequate Water Rights (< 100 mm deficit), Light Scarcity (100 – 300 mm deficit), Medium Scarcity (300 mm – 600 mm deficit), and Heavy Scarcity (> 600 mm deficit). There is less allocated water along the downstream section of Boise River, which also leads to higher water scarcity in the area (Figure 11). The northwest part of the study area experiences light to middle level water scarcity. Water scarcity is overall not serious in the Treasure Valley, however, could pose a problem in the relatively dry years such as 2007, 2008 and 2013.

Figure 11: The spatial distribution of the annual unsatisfied irrigation maps averaged over the simulation period. The domain that is within the thick outline is Black Canyon Irrigation District, which receives additional irrigation water from outside of the domain, where the water scarcity is overestimated.

~~The spatial distribution of the annual unsatisfied irrigation maps averaged over the simulation period. The domain that is circled is Black Canyon Irrigation District, which receives additional irrigation water from outside of the domain, where the water scarcity is overestimated.~~

On average, ~ 80.1% irrigation demand could be satisfied from 2006 to 2013, with an unsatisfied irrigation rate about 5.1 m^3/s for the whole irrigation area. However, the unsatisfied irrigation amount varies greatly between years. For example, in 2011 when the annual precipitation is higher than normal (Figure 12), only an annual average of 3.4 m^3/s irrigation amount is

Formatted: Normal, Justified, Space Before: Auto, After: Auto unsatisfied in the Treasure Valley, while in 2013 when the annual precipitation is lower than normal, the annual averaged unsatisfied irrigation amount doubled to about 5.9 m^3/s (Figure 9). The Mediterranean climate pattern produces dry-hot summers which, even in the wettest years, some degree of unmet water potential irrigation use.

Figure 12 Annual precipitation amount calculated at Boise Air Terminal (Station ID: 7268104131). Precipitation is calculated based on water year since irrigation in each calendar year is mainly affected by the precipitation during the spring and last winter.

While the water rights appropriation rate reflects the irrigation district regulation, the allocated rate also considers the biophysical demand, and has the capacity to reveal where the current water rights are not sufficient for biophysical use. For example, the areas along downstream Boise River experience a relatively higher water scarcity (Figure 11). Since the Boise River has abundant water to extract during the irrigation season as shown in the discharge figures (Figure 4), the water scarcity is mainly due to the water right constraints. While this area is ascribed to be agricultural land, the area is mainly used for grass/pasture (Figure 13), which does not require much irrigation. Should these areas be converted to irrigated agricultural lands, they will need a larger water right allocation to support crops. This illustrates the value of spatially explicit demand-based water allocation and associated patterns to understand the irrigation water use dynamics.

Figure 13 The spatial distribution of crops and grass/pasture in the agricultural area of the Treasure Valley.

4.1.2 The model indicates irrigation inefficiency through the simulation of demand-based water allocation and the actual water use

Demand-based water allocation rates and the actual water use vary significantly. The allocated water in an IDU is determined by the IDU water demand, the water availability in the stream and water rights allocation rate and priority. The IDU water demand is calculated for irrigated lands based on the potential ET rates and the water loss coefficient. However, the actual water use by the farmers is usually more arbitrary relying on their experience, their irrigation methods and the economic expectations, and is a complex function. Application efficiencies for traditional furrow-irrigated systems supplied by siphon tubes or gated pipe range between 30 - 40%, with efficiencies of 50 - 60% percent possible with excellent management [*Neibling*, 1997]. A large amount of water is wasted even in this water-limited environment. The simulated multi-year average of allocated surface water is ~ 2.0 acre-feet per acre. This number is in the lower range of the allotted irrigation water by the Boise Project Board of Control which is about 2 – 3 acre-feet per acre in normal years for farmer use. This can also be validated by the diverted amount of water from the New York Canal (Figure 5), with an overall slightly underestimation but very good match between simulations and observations (correlation coefficient of 0.92). Considering that the water release at the operational level normally relaxes the biophysical demands and varies annually, our simulated irrigation water amount is in the right scale.

4.2 Model Limitations

While the model appears to be an effective tool to express spatially explicit water rights based allocation, there are some important features not captured by the model. Specifically, during the dry years, e.g., 2007 and 2013, the model produces higher simulated discharge compared to the observations at the Parma River gage during the irrigation season. There are a number of reasons for these deviations in the model: (1) Groundwater use is currently assumed to be unlimited, leading to extra amount of water recharged into soil layer. Although this reflects the current groundwater abundance of the study area, it does not maintain the water balance after groundwater irrigation, and may lead to larger simulated stream discharge at the downstream of the irrigation area. However, since groundwater irrigation counts for a very small portion of the irrigation water use, we intend to simplify the model at this stage by assuming an unlimited groundwater supply. (2) The diversion of water in many canals are actually operated as constant flows, differing from the demand-need diversion rates of the model. As such, it is implausible to find a perfect match between observations and simulations. (3) The model is limited to the Boise River watershed and only water within that watershed is considered. However, there is some transfer into the basin from the adjacent watershed. This is especially important for the northwest part of the Treasure Valley (mainly Black Canyon Irrigation District) where the model predicts water scarcity (Figure 11). In reality, some water is pumped from Payette River outside of the boundary to irrigate this area so it is very likely that the model is underestimating the water allocation and exaggerating the water scarcity in this area. (4) The model is semi-conceptual, and ignores some minor consumptive water use. For example, the water that is incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment.

A second area where the model underperforms is capturing some flow details at the beginning of each year. Local agencies tend to empty the reservoirs in the winter time for spring flood protection, while the model ignores this local human operation. In addition, irrigation water use is not only affected by weather conditions and irrigation at the current time step, but also affected by a longer term climate and surrounding environments. Considering that the surface water source is mainly from snow melt in the upper Boise River Basin, the available water of an irrigation season in the study area is strongly affected by the precipitation from the current spring and the previous winter in the upper watershed. As such, the annual summation of the allocated water is complex and has no linear relationship with the annual precipitation amount. For example, ~~is a complex nonlinear issue as shown in Figure 9. For example,~~ 2007 is a dry year, but the allocated water is still relatively high (Figure 9) due to the high precipitation rate in 2006 (Figure 12) which releases abundant snow melting from the upper watershed during the earlier irrigation season of 2007.

Nonetheless, Boise River has never been totally drained out in a single day during the simulation period, and has abundant water to be diverted. The river joins the Snake River and then flows north towards mostly public lands. While accurate simulation of water diversion is important in the Treasure Valley, it is not critical further downstream for either human use due to the low population size or environmental protection due to the relative abundance of water in the Snake River in Oregon and Washington. ~~M~~More accurate discharge downstream (e.g., at the Parma station) matching the historical record is not a deciding factor for irrigation activities in ~~the area~~the Treasure Valley, and the downstream water balance mismatch is currently not an influencing factor for irrigation distribution.

Despite the limitations and challenges, the results generated by this research have successfully integrated irrigation activities into a hydrological model and can serve as a good start for further studies. The current study also proves that the integrated modeling work can provide sufficient spatial and temporal details to nevertheless provide useful insights into possible management strategies for water use in the Treasure Valley.

4.3 Insights and future work

This work is built under a larger on-going modeling framework that aims to integrate complex social and biophysical processes and reveals the requirement of multi-disciplinary coorporation.

Our experience suggests that deploying such an interdisciplinary approach is by no means a trivial task. During our research, a large team of scientists, engineers and stakeholders continuously discuss and construct an agreement on the study domain which reflects both the watershed boundary and political boundary, the research questions, the temporal scales and the complexity of the work. Knowledge from local stakeholders are also borrowed to help justify the design of the model. This research effort is an important step forward towards the solution to the cultural and historical barrier to the integration across disciplines [*Hamilton et al.*, 2015].

As the first report of the modeling fruit, in this paper, we are using historical downscaled climate data here to represent the climate, and the parameter set is only suitable for this specific case. For the future research of water availability projection, a suite of different climate change scenarios will be incorporated. Future modeling of this method will highlight changes in water deficits over time by dynamically simulating IDU water demand and water availability. Water rights are also going to be dynamically allocated with adoptive strategies when water scarcity is more severe. ~~In addition, o~~Other important factors such as urban growth, land use and land cover change, and crop choice will also be integrated into the future model with the feedback of stakeholders. In addition, the decision making of stakeholders has its own complexity and has to be simplified in the current model [*Noël and Cai*, 2017]. The heterogeneity of decision making, which is often overlooked due to lack of data, has important implications and deserves better representation.

5. Conclusion

This study integrates spatially and temporally explicit irrigation activities into hydrologic cycles, connecting agriculture, water rights and hydrologic processes in the semi-arid Treasure Valley. The model results reveal the spatial and temporal patterns of irrigation water use, and areas where current water rights are not always able to support irrigation demand. The model is useful in that it can be used to diagnose places of use and times where allocated water is likely insufficient to meet agricultural water demands, and inform future water management decisions. The modeling framework is extensible and allows not only for the model to be subjected to future scenarios of urbanization and climate change, but also as a tool for evaluating alternative future scenarios of water management policies and actions. The model also indicates the current knowledge gap in water use between the water rights based diversion rate and the actual irrigation water consumption, including the complexity of human activities and the inability to fully capture the discharge over dry years.

Author contributions: ~~Bangshuai Han and~~ Alejandro N. Flores and Bangshuai Han designed this research and interpreted the results. John Bolte and Kellie B. Vache provided technical support with debugging help. Bangshuai Han prepared the manuscript with the help with Shawn Benner, Alejandro N. Flores, and get agreement for submission with all co-authors.

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Table 1 Datasets used in the model

Input Data	Data Sources	Dates/Spatial Resolution	Used in Model Components	Url
Land use/land cover	National Landcover ~~d~~Dataset ~~(NLCD)~~	2011/ 30 m	Evapotranspirat-ion	http://www.mrlc.gov/nlcd2011.php
Streams/canals/Water bodies	NHDPlus V2	2012	Building stream network and flow routing	http://www.horizon-systems.com/nhdplus/NHDPlusV2_17.php
Downscaled climate data	U of Idaho METDATA ~~(4 km resolution)~~	2006-2013 / 4 km	Evapotranspirat-ion	http://cida.usgs.gov/thredds/catalog.html?dataset=cida.usgs.gov/thredds/UofIMETDATA
Daily stream discharge	USGS Instantaneous Data Archive	2006-2013	Hydrology model calibration and validation	http://nwis.waterdata.usgs.gov/nwis/rt
Digital elevation model	NED ~~(30 m resolution)~~	N/A / 30 m	Building HRU	http://nationalmap.gov/elevation.html
Water rights	Idaho Dep~~ar~~t~~ment~~. of Water Resources	2010	Irrigation (Watermaster)	http://www.idwr.idaho.gov/ftp/gisdata/Spatial/WaterRights

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Table 2 Crop categories used to approximate the land use categories in the ET calculation

Land use category	**Approximated Crops in ET calculation**
Agricultural	Alfalfa
Developed land	Bare land
Forest	Poplar
Shrubland	Sagebrush
Herbaceous	Average of Cheatgrass, bunch grass and bromegrass

Table 3 Parameters used, the range considered for calibration and the calibrated values

Routine	Parameter	Description	Units	Range Considered	Calibrated Value
Snow Routine	TT	Threshold temperature	ºC	-2.0 - 2.0	0.4
	CFMAX	Degree-day factor governing maximum snowmelt rate	mm/ºC /day	1.0 - 6.0	3.6
	SFCF	Snowmelt correction factor	-	0.5 - 3.0	2.2
	CFR	Refreeze coefficient	-	0.05	0.05
	CWH	Water holding capacity of snowpack	-	0.1	0.1
Soil and Evaporation Routine	FC	Maximum depth of water in soil water reservoir	mm	395	395
	LP	Soil moisture value above which actual ET = PET	mm	200.0	200
	WP	Wilting point in soil for ET to occur	mm	147	147
	BETA	Shaping Coefficient	-	1.0 - 6.0	2.6
Ground-water and Response Routine	PERC	Percolation coefficient	per day	0.1 - 10.0	6.6
	UZL	Threshold for K0 to outflow	mm	10.0 - 500.0	240.7
	K0	Recession coefficient	per day	0.1 - 1	0.7
	K1	Recession coefficient	per day	0.01 - 1.0	0.07
	K2	Recession coefficient	per day	0.0001 - 1.0	0.0002

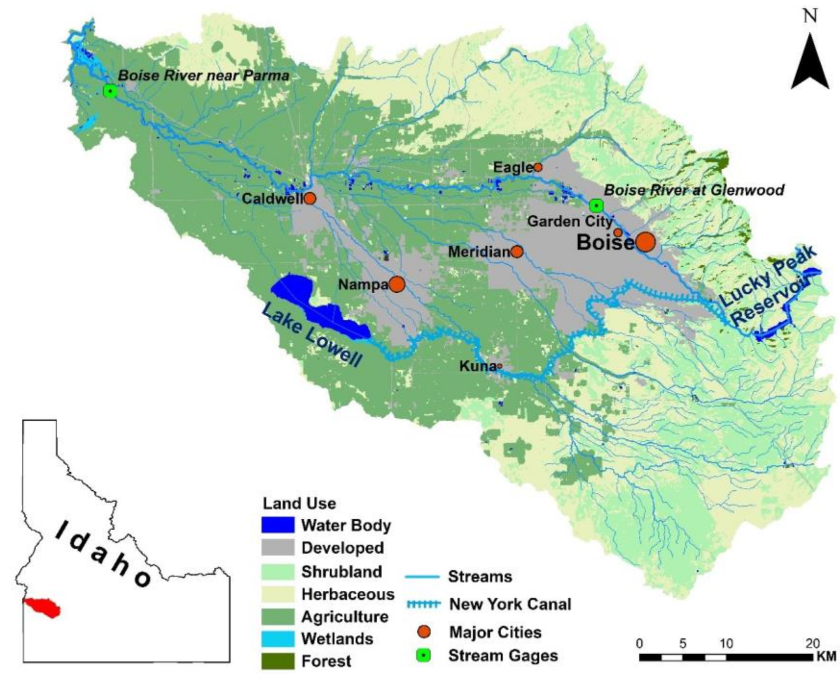


Figure 1 Study Area: The Treasure Valley which is located at Southwest Idaho, with Idaho's three largest cities and complex agricultural activities.

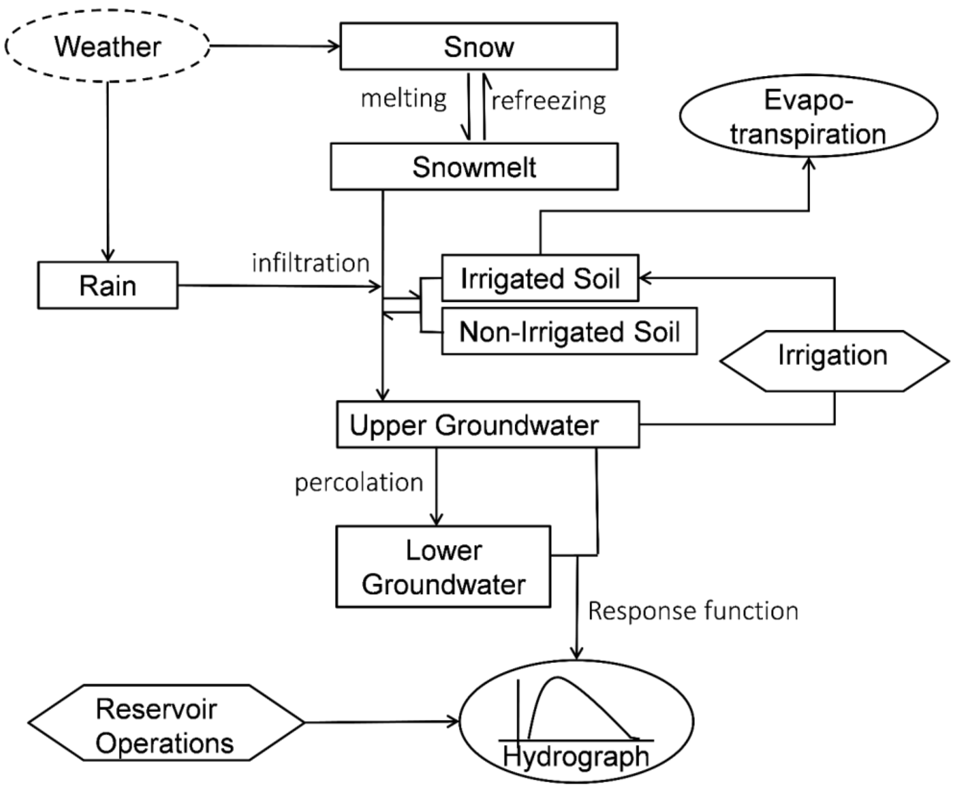


Figure 2 Flowchart of the Flow model in Envision. Note the human activities influencing water availability. Water is distributed by the local water rights data (irrigation activities), and is also constrained by the reservoir operations.

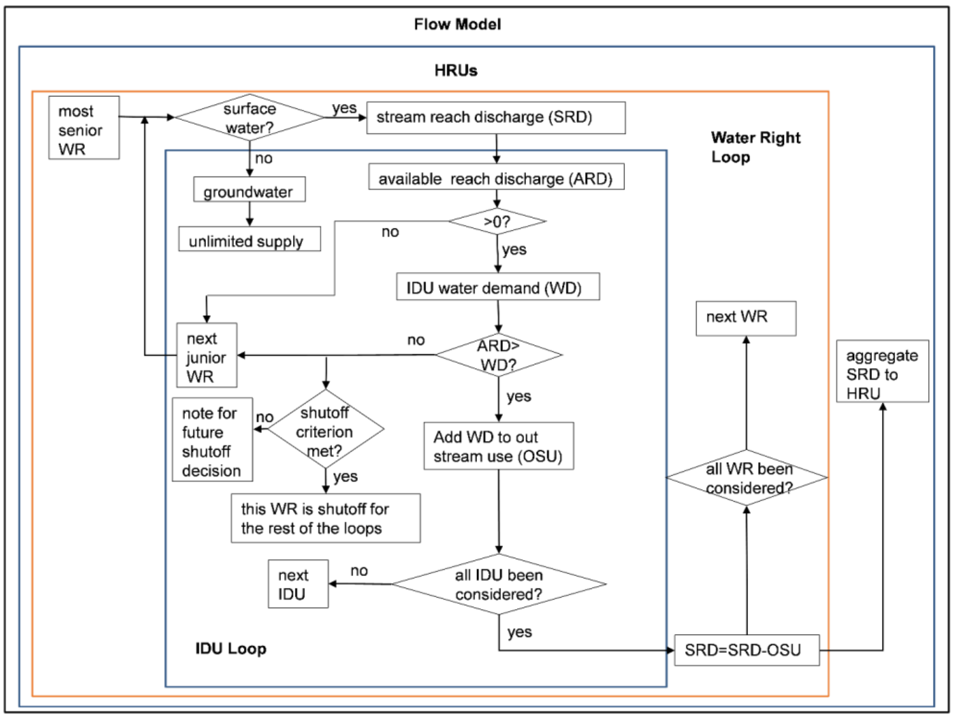
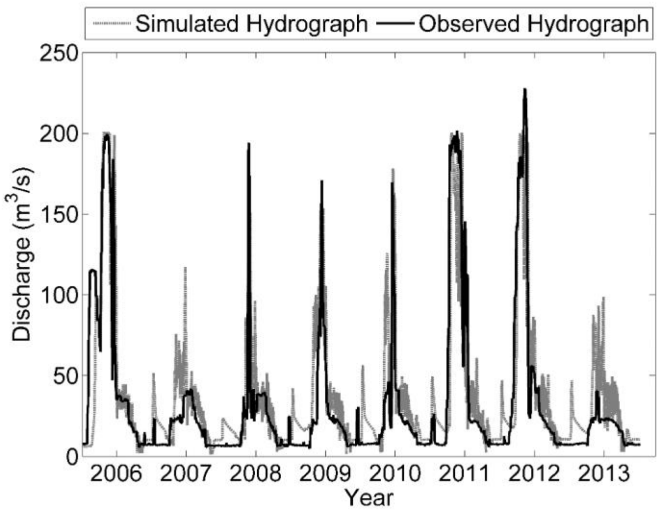
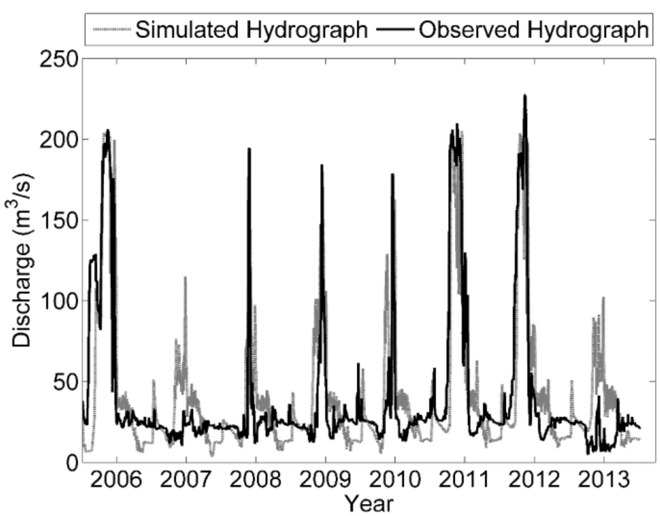


Figure 3 Flowchart of the water right loop in Envision. Each water right is first appropriated for each IDU it applies to. At each flow time step, the stream reach discharge is then aggregated to the HRU level, and used for the next time step.





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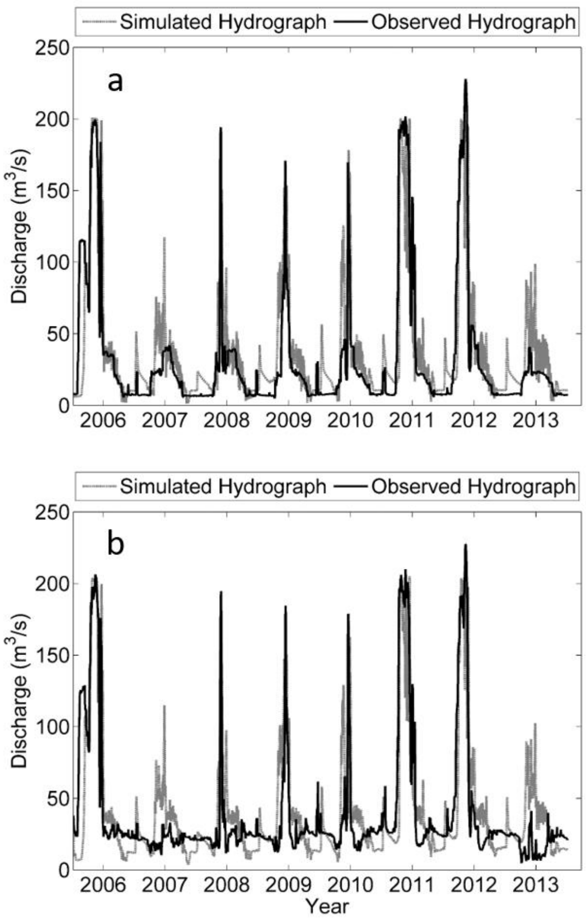
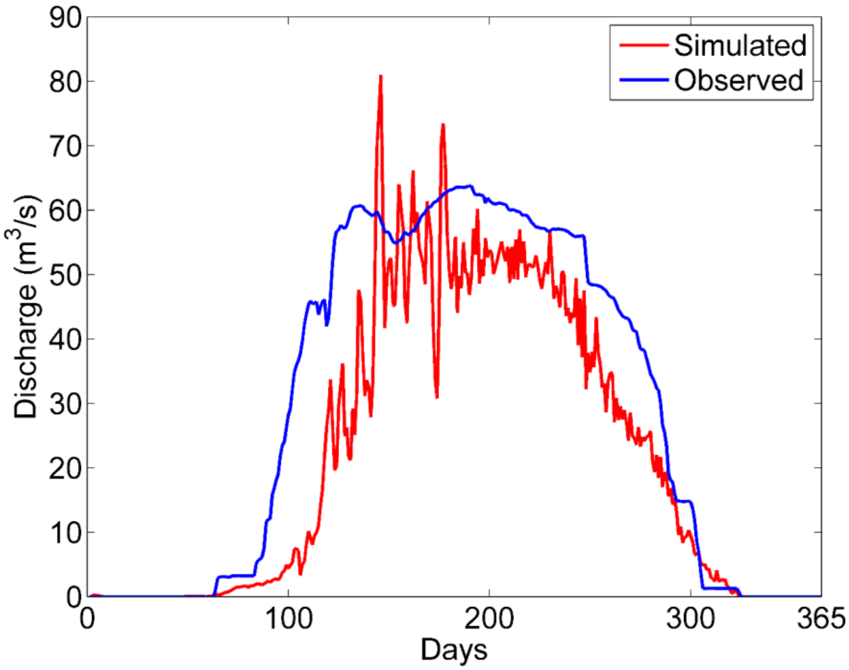


Figure 4 Simulated discharge and the observations during the calibration (2006 ~ 2009) and validation periods (2010 ~ 2013) at the Glenwood Station of Boise River (Upper Panel a) and Parma Station of Boise River (Lower Panel b).


Simulated
Observed
Discharge (m³/s)
Days
0
10
20
30
40
50
60
70
80
90
0
100
200
300
365

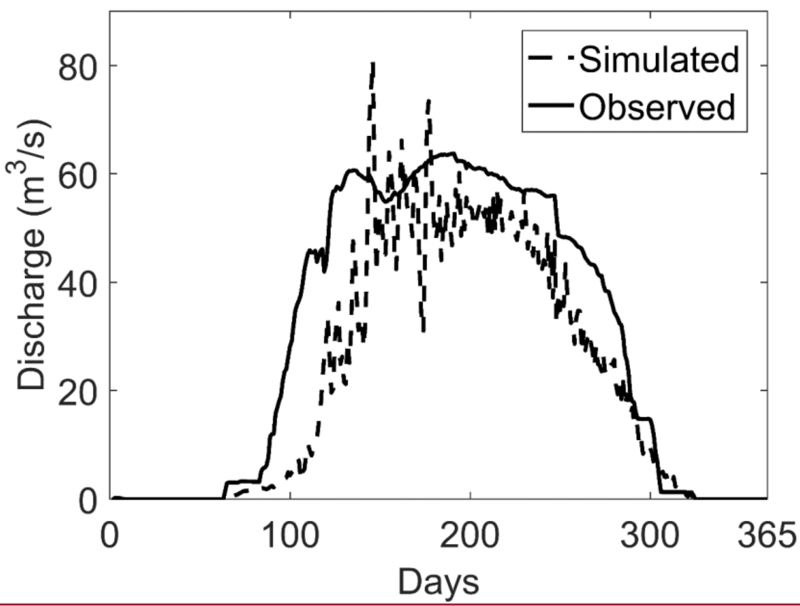


Figure 5 Simulated irrigation amount and the observations averaged over the years of 2006 ~ 2013 at the New York Canal. The solid lineBlue color lines shows the observed are daily discharge rate in m^3/s, and the dashed red color lines are shows the cumulative simulated discharge in m^3/s.

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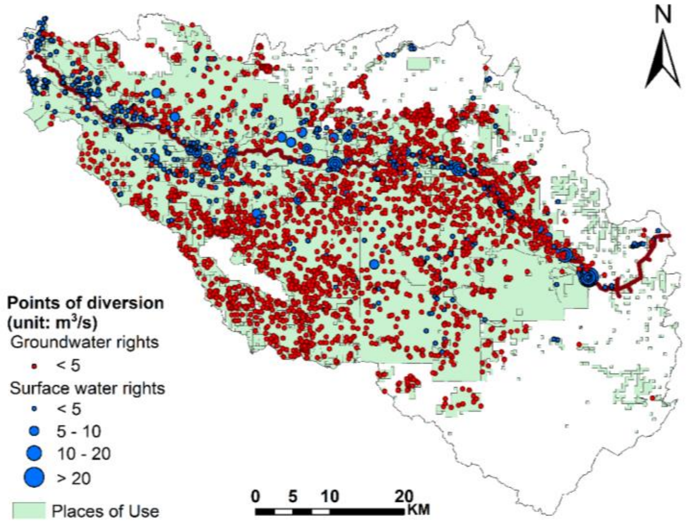
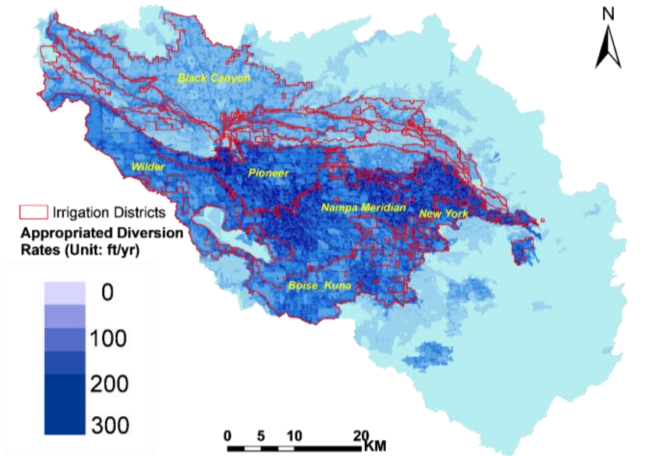


Figure 6 The maximum allowed diversion rates and the spatial distribution of the Points of Diversion (PODs). Note that multiple diversion PODs overlap at the New York Canal diversion places, and the water diverted from New York Canal serves as the main surface water resources for the agricultural areas.


N
Black Canyon
Wilder
Pioneer
Nampa Meridian
New York
Boise_Kuna
Irrigation Districts
Appropriated Diversion Rates (Unit: ft/yr)
0
100
200
300
0 5 10 20 KM

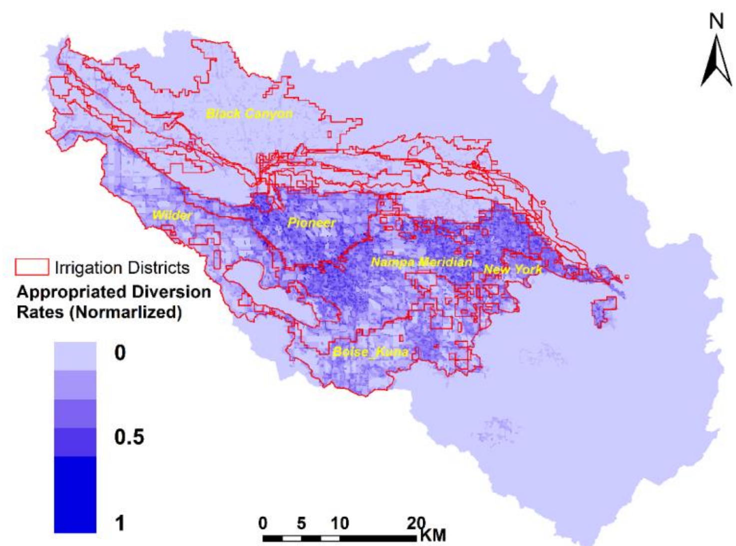
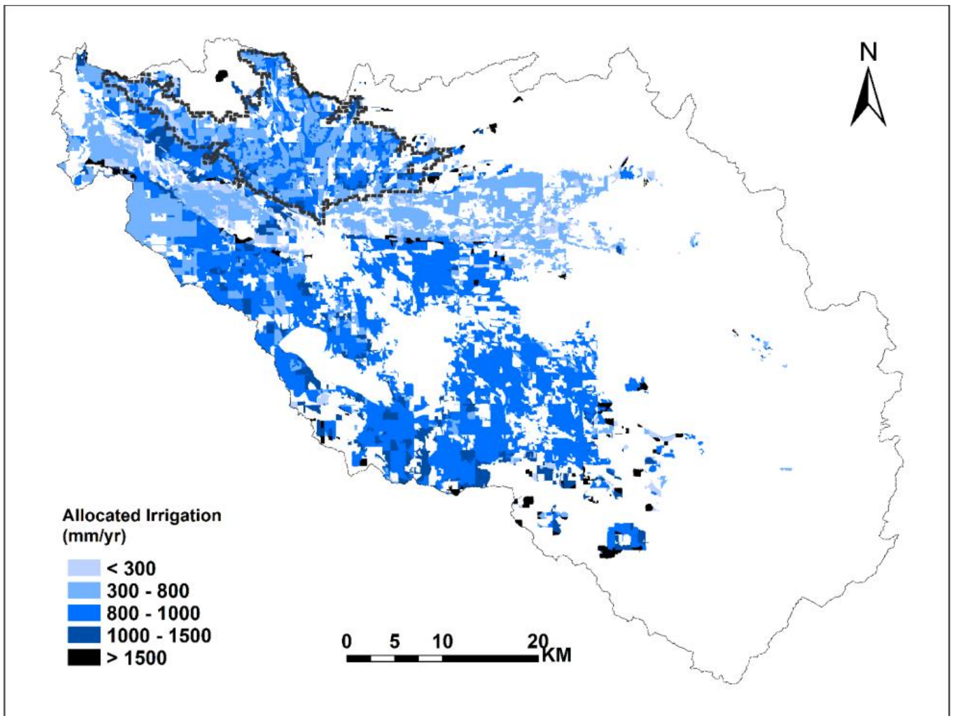

N
Black Canyon
Wilder
Pioneer
Nampa Meridian
New York
Boise_Kuna
Irrigation Districts
Appropriated Diversion Rates (Normarlized)
0
0.5
1
0 5 10 20 KM

Figure 7 The annual appropriated diversion rates normalized ~~calculated~~ based on water rights maximum allowed diversion rates and place of use, indicating the relative spatial distribution of potential usable water. The irrigation district boundaries and the names of major irrigation districts are also shown.


N
Allocated Irrigation
(mm/yr)
< 300
300 - 800
800 - 1000
1000 - 1500
> 1500
0
5
10
20
KM

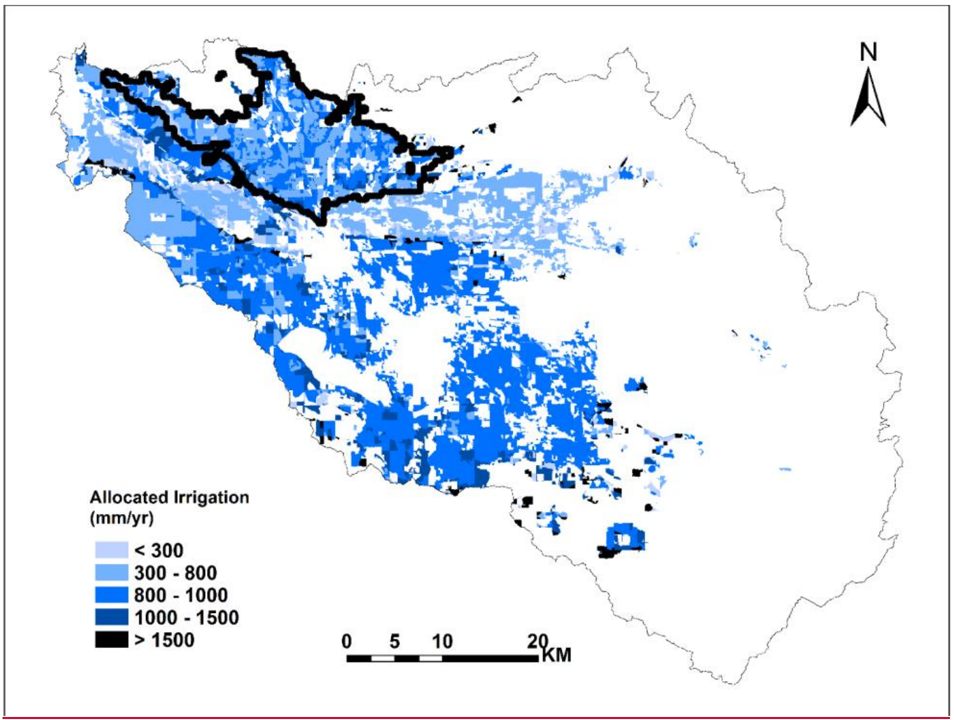


Figure 8 The spatial distribution of the annual allocated irrigation water averaged over the simulation period. The domain that is within the thick dottedoutline circle is Black Canyon Irrigation District, which receives additional irrigation water from outside of the domain, where the water allocation is underestimated.

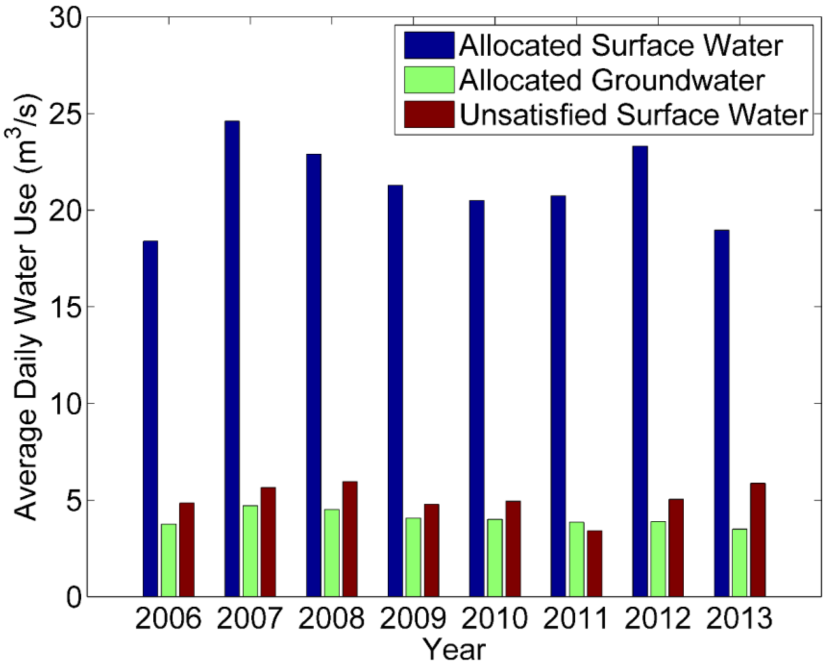


Figure 9: Average daily allocated surface water, groundwater and unsatisfied surface water use for each year.

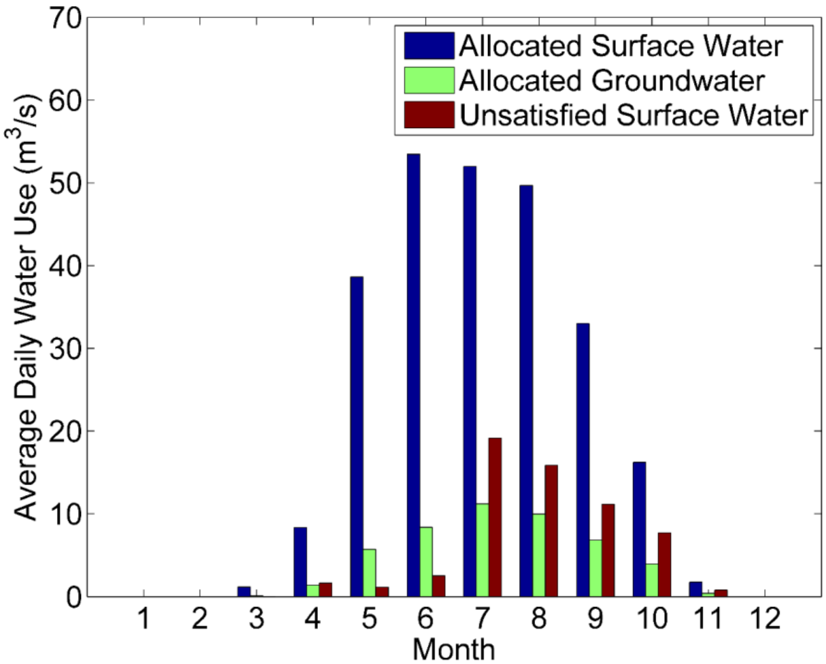
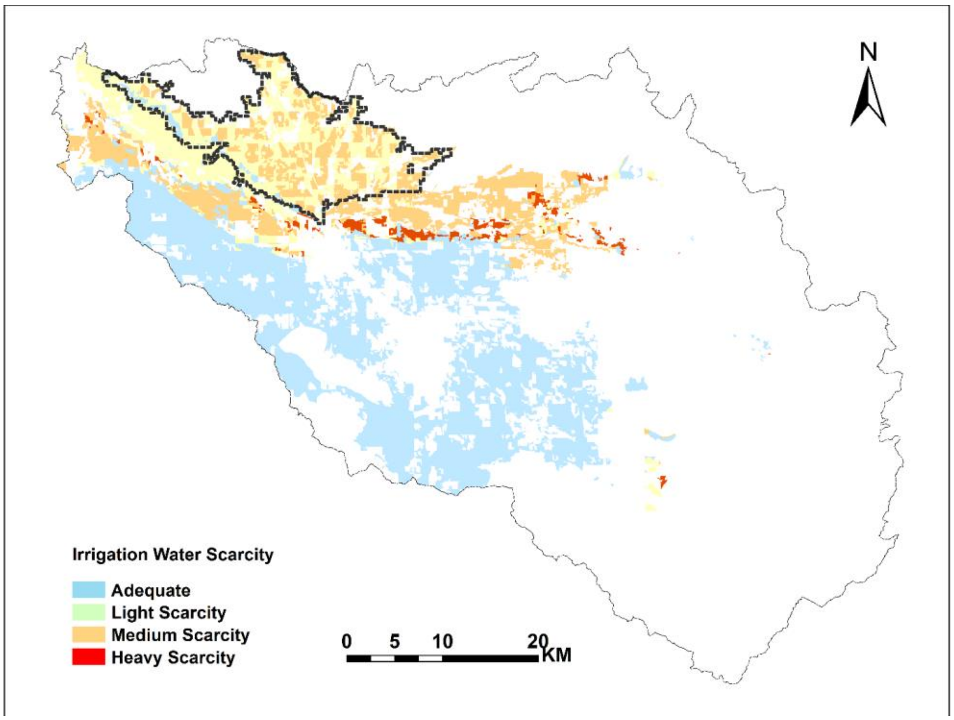


Figure 10: Average daily allocated surface water, groundwater and unsatisfied surface water use for each month from 2006 to 2013.


N
Irrigation Water Scarcity
Adequate
Light Scarcity
Medium Scarcity
Heavy Scarcity
0 5 10 20 KM

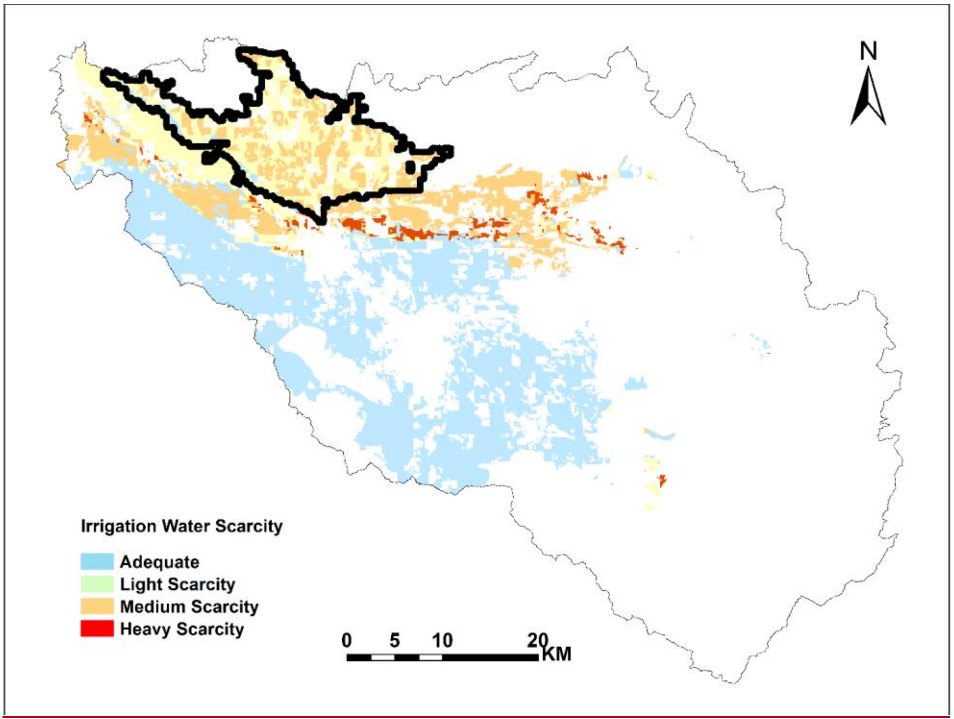


Figure 11: The spatial distribution of the annual unsatisfied irrigation maps averaged over the simulation period. The domain that is within the thick outline ~~circled~~ is Black Canyon Irrigation District, which receives additional irrigation water from outside of the domain, where the water scarcity is overestimated.

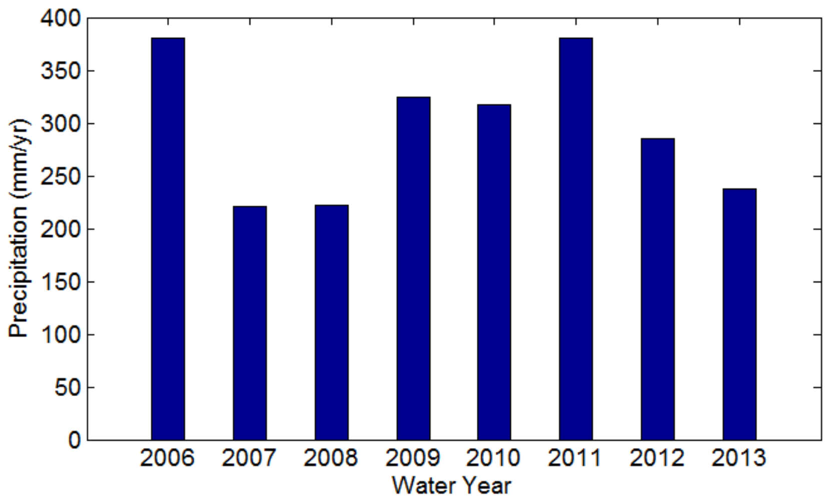


Figure 12 Annual precipitation amount calculated at Boise Air Terminal (Station ID: 7268104131). Precipitation is calculated based on water year since irrigation in each calenda year is mainly affected by the precipitation during the spring and last winter.

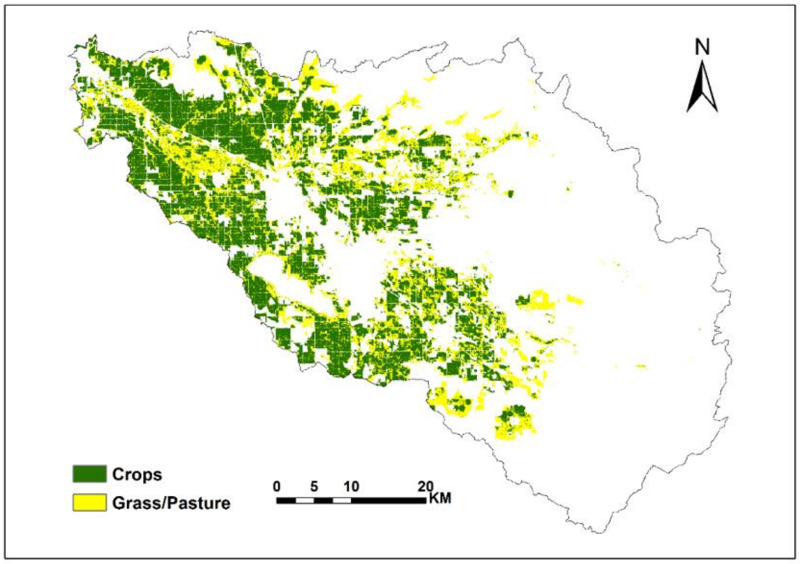


Figure 13 The spatial distribution of crops and grass/pasture in the agricultural area of the Treasure Valley.