Hydrologic Externalities and Water Transfers in a Conjunctively Managed Water System

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Allocation of water to the highest marginal value users can generate economic gains relative to Prior Appropriations-based distribution. However, water reallocation schemes can generate third party externalities which prohibit such transfers. A spatial and temporal, integrated hydro-economic model is used to assess the gains from redistributing water use across agricultural irrigators relative to the Prior Appropriations-based allocation taking into account externalities which such redistribution can produce. The model optimizes the redistribution of water use across space and time such that the return flows in various segments of the watershed over time do not decrease relative to the flows produced by the Prior Appropriation-based allocation. For the considered water shortage scenarios in Idaho's Eastern Snake River Plain, the reallocation of water use, subject to third party externalities, can generate 8% to 16% increase in total annual benefits relative to Prior Appropriation-based allocation.

Hydro-economic Optimization of Water Use Reallocation under Binding Hydrologic Externalities

Introduction

In addition to surface water shortages due to draughts, groundwater levels in many aquifers in the Western US have also been declining due to increased groundwater pumping, reduced recharge, and prolonged droughts. Decreases in surface and groundwater water supplies, combined with lack of adequate property right institutions in many cases have led to numerous conflicts involving lengthy and costly administrative and legal proceedings (Slaughter and Wiener, 2007; Baker and Willing, 2006; Jaeger, 2004; Boehlert and Jaeger, 2010). For example, in 2009 in response to a water call placed by senior water users, Idaho Department of Water Resources issued curtailment orders to junior irrigators potentially affecting 41 thousand acres of irrigated land in the Snake River plain. Similar curtailment order was issued in 2014 and another one is currently under consideration potentially affecting 150 thousand acres of irrigated agriculture (IDWR, 2014)[1]. Such legal disputes are indicative of deficiencies in property right definitions and/or enforcement, which are essential for achieving economically efficient distribution.

Social welfare maximizing distribution of a scarce resource, like water, is such that marginal benefits across different users are equal - the condition sometimes referred to as "equimarginal principle" (Elbakidze and Cobourn, 2013). In such allocation, consistent with the criterion of Potential Pareto Optimality (Griffin, 1995), it is impossible to redistribute the scarce

[1] Water use disputes have been documented elsewhere in the western US. Irrigators in Nebraska (Mieno, 2014) were curtailed following lawsuits filed by Kansas irrigators. Montana's lawsuit against irrigators in Wyoming was ruled in favor of Wyoming irrigators (Fuller, 2014) thereby limiting water availability to Montana irrigators. Numerous lawsuits have also been filed in CA including but not limited to disputes between Indian Tribes and irrigators, and between irrigation districts and environmental groups.

resource across users such that the redistribution beneficiaries gain more than is forfeited by the losers of redistribution. The economists' preferred mechanism for achieving such distribution is a market with well defined, enforced, monitored, and transferrable water rights. Under such conditions, and in absence of significant transaction costs, Coasian bargaining produces social welfare maximizing distribution of the resource (Coase, 1960). This outcome is grounded in the first theorem of welfare economics which states that competitive market equilibrium is Pareto optimal (Myles, 1995). Clearly, the conditions required for achieving such competitive market equilibria are often not met in practice. As a result, resource utilization can be economically suboptimal in terms of Pareto or Potential Pareto optimality. In such cases, to maximize social benefits, one policy option is to invoke regulatory centralized distribution strategy which would mimic competitive market equilibrium in terms of equimarginality of benefits across users. The other option is to engage in development of technologies and institutions which would facilitate formation and operation of competitive markets including strengthening property rights and minimizing transaction costs associated with water trades.

In the Western US, water allocation is governed by the Prior Appropriation Doctrine (PAD), or "first in time, first in right", where water right seniority is assigned according to the adjudication date of the water right establishing beneficial use (Griffin 2006). The older the water right adjudication date, the greater the seniority. According to PAD, during water shortages senior water rights take precedence over junior water rights in terms of securing access to limited water supplies. Hence, in times of water shortages water users with relatively junior rights receive water only if adjudicated rights of relatively senior water users have been met.

In theory this mechanism of water distribution can produce an economically efficient outcome, not requiring redistribution, if relatively more senior water rights belong to water users with relatively high marginal values for water. In the context of agriculture, an allocation based on PAD would be economically efficient if irrigators with relatively more productive lands owned relatively senior water rights, *ceteris paribus*. In practice, however, relatively more productive lands often have relatively junior water rights. For example, as a result of settlement and development patterns that minimized diversion and conveyance losses, lands nearest to surface watercourses often have more senior water rights, regardless of soil productivity. Hence, relatively more senior water rights can in practice belong to users with relatively less productive land which may be located near a watercourse. Such distribution of water right seniority can potentially produce a suboptimal distribution of water use during shortages because water may not be available for junior users with relatively higher marginal values of irrigation water. In such cases economic efficiency may not be achieved unless water use is transferable, allowing water to be reallocated according to its highest marginal value product, barring associated legal barriers and other transaction costs (Wescoat 1985). This inefficiency becomes more important and costly as water becomes scarcer (Griffin and Hsu, 1993; Boehlert and Jaeger 2010), as is anticipated under many scenarios of climate change for many regions of the US.

On a limited scale, water markets, acting as a mechanism for optimizing water distribution, have been implemented in the United States and other countries (Hadjigeorgalis, 2009; Chong and Sunding, 2009). However, skepticism and practical barriers for water redistribution and trade persist. Third-party hydrologic externalities have been recognized in the economic literature as one of the major obstacles for implementation of water markets or other types of water transfer mechanisms (Young 1986, Howe et al. 1986; Chong and Sunding 2006). These externalities arise when a transfer of water use from one user to another has implications for fulfillment of water rights held by downstream users not involved in the transaction, or for fulfillment of rights allocated for environmental or in-stream flows.

The objective of this study is to illustrate an empirical modeling approach, which can be used for evaluation of regional water use (re)distribution policies taking into account third party hydrologic externalities associated with water use transfers. The model explicitly incorporates a set of constraints which restrict water transfers from generating third party hydrologic externalities. These constraints are expressed in terms of temporally and spatially explicit multidimensional hydrologic response functions and assure that the return flows at river reaches, predefined based on hydrologic watershed characteristics, are unaffected by water use reallocation. The objective is to identify potentially superior spatial distribution of water use relative to PAD-based distribution, such that the redistribution maintains the net return flows in all segments of the river to be equal to the net return flows produced by the PAD-based distribution of water use over time. Maintaining return flows at the river reach level is critical to ensure that third-party externalities generated by water use redistribution are minimized.

Based on the assumption of profit maximizing behavior of irrigators the spatially and temporally explicit, integrated hydro-economic mathematical programming model optimizes agricultural water use across space and time when water supplies are limited. The model maximizes total economic rents derived from the use of irrigation water subject to hydrologic, agronomic, managerial, and water right distribution specifications. The empirical model incorporates soil and crop-specific agricultural production functions (Martin, Gilley, and Supalla, 1989) and dynamic groundwater flow response functions (Cosgrove and Johnson 2005, Elbakidze et al. 2012) to determine spatially and temporally optimal distribution of irrigation water during water shortages. The model is used to examine the potential for redistributing

PAD-based allocation of water use across agricultural producers during water shortage consistent with the criterion of potential Pareto Optimality. We compare the outcomes of spatial and temporal distribution of water use under PAD-based curtailment of junior users across two scenarios: with and without reallocation of water use according to the highest marginal value. The primary appeal of the approach is that it can be easily applied in regions where the required spatial data on soil productivity and hydrologic connectivity are available. Such data are readily available for most agricultural production regions in the US.

The empirical analysis is done in the context of southern Idaho's Eastern Snake River Plain Aquifer (ESRPA) which generally is considered to be unconfined (Cosgrove and Johnson, 2005). The aquifer is a primary source of irrigation water for one of the most highly productive agricultural regions in the US (Ryu et al. 2012; Elbakidze et al 2012; Hoekema and Sridhar 2011; Ghosh et al. 2014; Contor and Taylor 2013). We extend the prior work in ESRPA in four important respects. First, we explicitly take into account third-party externalities of water transfers with respect to eleven hydrologically segmented reaches of the Snake River. Second, rather than using fixed irrigation efficiency coefficients for sprinkler and flood irrigation technologies we allow irrigation efficiency to vary with water use decisions and across crops and irrigation technologies to estimate consumptive use and return flows. Third, instead of using historically observed crop mix proportions as bounds to impose crop rotation constraints, we use spatially explicit crop rotation requirements based on input from local extension specialists. Historically observed crop mix data is only used for model validation. Fourth, we improve consistency of comparing the results from prior appropriation based curtailments with and without reallocation mechanisms by internally estimating consumptive use in both scenario simulations[2].

Economic Framework

According to PAD, at the time of water shortage regional water administrators are obligated to curtail junior water right users based on relative seniority of water rights to assure delivery of sufficient water to senior water rights holders. Suppose that at times of ample water supply, not requiring curtailment, each area *z* pumps $\bar{w}_z$ amount of water according to adjudicated rights. During water shortage and corresponding curtailment of most junior water users lasting τ periods, the maximum amount of water which can be pumped in each area *z* decreases by $\tilde{\bar{w}}_{z\tau}$ in each period. Hence each area can pump at most $\bar{w}_z - \tilde{\bar{w}}_{z\tau}$ amount of water according to PAD-based curtailment with no reallocation of water use. In such context, each unit *z* uses water according to,

$$\begin{aligned} &\underset{w_{z\tau}}{MAX} \left\{ \sum_{\tau=0}^{T} e^{-r\tau} R_{z\tau}\left(w_{z\tau}\right) \right\} \qquad \forall z, \tau \\ &S.T. \quad w_{z\tau} \le \bar{w}_z - \tilde{\bar{w}}_{z\tau} \end{aligned} \tag{1}$$

where, *r* is the discount rate, and $R_{z\tau}\left(w_{z\tau}\right)$ is profit of irrigation unit *z* in period τ as a function of applied water, w_{zt}. Problem (1) is solved for each unit z in period τ. The optimum levels of w_{zt} are implicitly defined by the first order conditions in (2) where $\mu_{z\tau}$ are shadow prices of irrigation water in zone z at time τ.

$$e^{-r\tau} R'_{z\tau}\left(w_{z\tau}\right) = \mu_{z\tau} \qquad \forall z, \tau \tag{2}$$

[2] Elbakidze et al. (2012) use exogenously estimated consumptive use values for evaluating prior appropriations based curtailment with no water reallocation mechanism. However, they use endogenously estimated consumptive use to simulate outcomes of the scenario where transfer of water use is allowed.

Assuming binding water availability constraints and nonzero Lagrange multipliers, each unit z pumps $\bar{w}_z - \tilde{\bar{w}}_{z\tau}$ amount of water. For a particular curtailment distribution scenario, let B_{kt} represent the change in return flow in area *k* over time as a result of strict PAD-based curtailment of junior users with no reallocation of water use. This amount of water that propagates to each segment *k* over time can be estimated as $B_{kt} = \sum_{z}^{Z}\left[\sum_{\tau=0}^{t} e\left(\tilde{\bar{w}}_{z\tau}, \alpha\left(w_{z\tau}\right)\right)\Psi_{z,k}^{t-\tau}\left(d_{z,k}\right)\right], \ \forall t,k$, where $\Psi_{z,k}^{t-\tau}$ is the hydrologic response function, which shows the amount of water received in area *k* in period *t* as a result of one unit decrease in consumptive use by entity *z* in period τ, or $t - \tau$ periods ago. The response function is presented in terms of transient hydraulic distance ($d_{z,k}$) between zone *z* and area *k* (Johnson, Cosgrove, and Lovell, 1998). The greater the hydraulic distance between entity *k* and entity *z*, the smaller the proportion of decrease in consumptively used water which propagates from entity *z* to the segment *k* over time. $e\left(\tilde{\bar{w}}_{z\tau}, \alpha\left(w_{z\tau}\right)\right)$ is the change in consumptively used water as a result of $\tilde{\bar{w}}_{z\tau}$ decrease in the amount of water pumped in area *z* in period τ. We are interested only in consumptively used portion of water that would have been pumped because change in consumptive use represents the net effect of reduction in pumping on the amount of water in the aquifer. The portion of the pumped water which is not consumptively used reverts back into the aquifer and does not impact groundwater levels. The change in consumptively used water depends on the amount of reduction in applied water $\tilde{\bar{w}}_{z\tau}$ and on irrigation efficiency α, which depends on the amount of applied water and shows the proportion of a unit of applied water that is consumptively used. This formulation ensures that only the portion of reduced pumping which would have been consumptively used under business as usual scenario (with no shortage or curtailment) can be counted towards additional return flow at segment *k* over time due to reduced pumping.

With PAD-based curtailment and reallocation of water use the objective is to maximize combined regional discounted profits subject to a set of requirements which state that each segment k receives at least B_{kt} amount of water as return flow. Hence, the optimization problem is,

$$\begin{aligned} &\underset{w_{z\tau}}{MAX} \left\{ \sum_{z}^{Z} \sum_{\tau=0}^{T} e^{-r\tau} R_{z\tau}\left(w_{z\tau}\right) \right\} \\ &S.T. \quad \sum_{z}^{Z} \left[\sum_{\tau=0}^{t} e\left(\bar{w}_{z} - w_{z\tau}, \alpha\left(w_{z\tau}\right)\right) \Psi_{z,k}^{t-\tau}\left(d_{z,k}\right) \right] \geq B_{kt}, \ \forall t,k \end{aligned} \tag{3}$$

The first order conditions (4) for this maximization problem implicitly define optimal water use in each area z at time τ.

$$e^{-r\tau} R_{z\tau}^{'}\left(w_{z\tau}\right) = \sum_{k} \sum_{t=\tau}^{T} \lambda_{kt} \Psi_{z,k}^{t-\tau}\left(d_{z,k}\right) e'\left(\bar{w}_{z} - w_{z\tau}, \alpha\left(w_{z\tau}\right)\right) \ \forall z, \tau \tag{4}$$

where $\lambda_{k\tau}$ are lagrange multipliers associated with the constraints that segment k has to receive at least B_{kt} amount of additional water at time t. The first order condition implies that the discounted marginal benefit of irrigation water for entity z at time τ is equal to the sum of shadow prices across k segments for each period from τ to T scaled by the corresponding response function, which links water use in z in period τ to every k in every period t following τ, and scaled by marginal reduction in consumptive use in z in period τ. First order conditions (2) and (4) can produce different optimal water use over time in each area z depending on the distribution of curtailments $\tilde{\bar{w}}_{z\tau}$, marginal consumptive use e, and response functions $\Psi_{z,k}^{t-\tau}$. In the empirical analysis we estimate the difference in total regional agricultural profits which such solutions may produce under particular water shortage scenarios.

The Empirical Model

The empirical analysis is done in the context of Eastern Snake River Plain where a highly transmissive aquifer represents the primary source of irrigation water for one of the most productive agricultural regions in the US. In the model the region is divided into 330 5x5 mile zones, each with up to six soil types which vary according to their productivity based on Natural Resource Conservation Service (NRCS) classifications (Figure 1); up to nine crops; two irrigation technologies (gravity and sprinkler); and two water sources (surface and ground).

The objective function is:

$$\pi = \sum_{c,z,s,it,ws,t} e^{-rt} \begin{bmatrix} P_{c,z} Y_{c,z,s,it,ws,t}\left(W_{c,z,s,it,ws,t}\right) X_{c,z,s,it,ws,t} \\ -C_{c,z} X_{c,z,s,it,ws,t} - CW_{z,it} W_{c,z,s,it,ws,t} X_{c,z,s,it,ws,t} \end{bmatrix} \qquad (5)$$

where *r* is the discount rate, $P_{c,z}$ is the price of crop c produced in zone z, $Y_{c,z,s,it,ws,t}\left(W_{c,z,s,it,ws,t}\right)$ is the yield per acre for crop *c* in zone *z* on soil type *s* with irrigation technology *it*, using water from source *ws*, at time *t*. *X* is the planted acreage and $C_{c,z}$ are the non-irrigation production costs per acre for crop *c* in zone *z*. $CW_{z,it}$ are variable irrigation costs in zone *z* of an irrigation technology *it*. *W* is the amount of water applied per acre. The model endogenously determines what, where, and how much to plant (*X*), and how much to irrigate (*W*) per acre.

The production functions (equation 6) are formulated following Martin et al. (1989) and express per acre yield, *y*, as a function of applied irrigation water, *w*. *Ym* is maximum crop yield under optimal amount of applied water. *Yd* is dry yield with no irrigation. *Wm* is maximum irrigation depth which produces *Ym*. *ETm* is evapotranspiration at *Ym*, and *ETd* is evapotranspiration at *Yd*. Similar production functions have been used in prior studies including but not limited to Elbakidze et al. (2012) and Palazzo and Brozovic (2014).

$$Y_{c,z,s,it,t} = Ym_{c,s} - \left(Ym_{c,s} - Yd_{c,s}\right)\left(1 - \frac{W_{c,z,s,it,ws,t}}{Wm_{c,s,it}}\right)^{\frac{Wm_{c,s,it}}{ETm_{c,s}-ETd_{c,s}}} \qquad (6)$$

The model solutions are subject to crop planting rotation constraints. The purpose of the rotation constraints is to restrict the model solutions to adhere to implicit production resource limitations and agronomic rotation requirements. In practice farmer decisions pertaining to planted acreages of various crops are subject to requirements, including but not limited to pest management and soil quality considerations. In addition, the rotation constraints implicitly reflect crop planting rotation patterns due to production resource constraints including capital, labor, etc. Unlike previous studies, which use historically observed crop mix proportions as bounds for simulated crop planted acreages to reflect rotation requirements (Elbakidze et al. 2012, Adams et al. 2003, Schneider et al. 2007, McCarl et al 1982), in this study we explicitly specify crop acreage rotation requirements based on input from industry experts and extension specialists across the region. Equation (7) shows the rotation constraints

$$\sum_c X_{c,z,s,it,ws,t} * RC_{ct,rt,c} \leq 0 \qquad \forall\, ct, z, s, it, ws, t \qquad (7)$$

where $RC_{ct,rt,c}$ is the proportional rotation coefficient for county *ct*, rotation specification *rt*, and crop *c*. Unlike Elbakidze et al. (2012), where the rotation constraints are expressed at the county level, the rotation constraints here are imposed for each combination of zones, soil classes, irrigation technologies, water sources, and years. This representation is superior to the formulation in Elbakidze et al. (2012) because this formulation disallows repeated planting of crops according to land productivity disregarding rotation requirements at soil class level while satisfying the rotation constraints at county level. Instead, the explicit rotation constraints in this model are imposed for production activities on each combination of soil classes, water sources, and irrigation technologies in each zone according to rotations specified at the county level[3]. Another advantage of the crop rotation specification used in this study is that no requirements are placed for lower bounds of crop planted acreages. The use of historically observed crop mix proportions for setting the limits on crop acreages, as done in prior literature, implies that planted acres of particular crops can not be lower than what has been observed in the past. Equation (7) does not place such bounds on planted acreages. Water availability scenarios not observed in the past can reasonably be expected to produce less planted acreages for some of the crops than what has previously been observed.

Planted acreage is also restricted not to exceed available amount of soil of particular type, irrigated using particular water source and using particular irrigation technology.

$$\sum_{c} X_{c,z,s,it,ws,t} \leq Land_{c,z,s,it,ws} \qquad \forall z, s, ws, it, t \qquad (8)$$

In this model irrigation efficiency used to compute consumptive use is endogenously determined depending on the amount of water applied rather than using fixed irrigation efficiency for flood and sprinkler irrigation regardless of the amount of water applied. The variable specification of irrigation efficiency allows the model to more accurately reflect the relationship between applied irrigation water and irrigation efficiency when estimating consumptive use per zone *z*. This relationship is expressed in equation (9). The variable irrigation efficiency is used to estimate consumptive use per zone according to equation (10).

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[3] As $RC_{ct,rt,c}$ does not vary by s, the same rotation constraints within a county is imposed for various soil types across zones z wi. It is likely that rotation specification could differ depending on soil type. However, this level of specificity was not possible to include at this stage given the type of input available from extension agents and industry specialists who provided representative rotation constraints by county. Nevertheless, county level rotation practices reported by the extension specialists are reflective of soil distributions in each county. Therefore, at county level our specification reflects a representative rotation across all land types in the county.

$$IE_{c,z,s,it,ws,t} = \frac{\frac{Y_{c,z,s,it,t}(w)}{Ym_{c,s}} ETm_{c,s} - ETd_{c,s}}{w_{c,z,s,it,ws,t}} \qquad (9)$$

$$CU_{z,t} = \sum_{c,s,it,ws} X_{c,z,s,it,ws,t} * W_{c,z,s,it,ws,t} * IE_{c,z,s,it,ws,t} \qquad (10)$$

Consumptive use per zone is used in combination with hydrologic response functions to determine the amount of water that propagates to river reach *k* at time *t* as a function of reduction in pumping in zone z in period τ, or $t - \tau$ periods ago relative to pumping in business as usual scenario. The steady state hydrologic response functions (Cosgrove and Johnson, 2005; Cosgrove et al., 2006; Cosgrove and Johnson, 2004) indicate the amount of water that becomes available over time at a particular river reach *k* as a result of reducing consumptive use in any particular zone *z* in ESPA in a given period. Figure 2 shows three response functions as an illustration. The three response function curves show the effects of depositing one unit of water in zones A, B, and C on one of the eleven river reaches over time in percentage terms.

Data

The model includes nine most commonly produced crops in the region: wheat, corn grain, corn silage, barley, sugar beets, dry beans, alfalfa, potatoes, and pasture. Crop prices, production costs, and irrigation costs in various regions of ESRP are obtained from the University of Idaho extension service's crop enterprise budget reports (2013). County-level historical crop mixes are used to validate model results (USDA NASS, 2013). Growing season precipitation, maximum available precipitation stored in root zone at planting, root zone depth, seasonal ETm (full-irrigation evapotranspiration), and maximum yields of fully irrigated crops are obtained from

Web Soil Survey (NRCS, 2010), the AgriMet weather database (USBR 2013), and University of Idaho Extension publications (Allen and Robison, 2007), as well as personal communications with extension agents. Dry (non-irrigated) yield is estimated using ETm, ETd (evapotranspiration under dryland conditions), and Ym (crop yield under full irrigation) (Doorenbos and Kassam, 1979; Allen et al., 1998; Martin, Gilley and Supalla, 1989). ETd is calculated following Doorenbos and Kassam (1979) and Ponce (1989). Irrigation depths required for maximum yields are estimated using ETm and the consumptive-use fraction of applied irrigation water (Doorenbos and Kassam, 1979; Martin, Gilley and Supalla, 1989). Acreages of each soil types across zones are obtained from Soil Data Mart (NRCS, 2010), and data on irrigation technology and water source per zone are obtained from Eastern Snake Plain Aquifer Model (ESPAM) (Cosgrove, Contor, and Johnson, 2006). Hydrologic response functions are obtained from ESPAM[4]. Based on the ESPAM specifications, each zone has eleven hydrologic response functions relative to each of the eleven reaches along the Eastern Snake River.

Empirical policy analysis

For illustration purposes, potential reallocation of water use is examined for a hypothetical water shortage scenario where irrigators junior to January 1973 priority date are curtailed[5]. ESPAM and IDWR water right database was used to obtain acreage amounts which would be

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[4] Hydrologic response functions are held constant over the modeling horizon. It is possible that if groundwater levels change than the dynamic and spatial properties of the response functions may also alter. For the cases where such changes may be significant and empirical estimates are available, the empirical model can be modified to accommodate evolving response function properties.

[5] In 2009 a curtailment order was issued requiring holders of groundwater rights Junior to Nov 16, 1972 to stop diverting water under those rights. In 2014 a similar curtailment order was issued to holders of groundwater rights with priority date junior to July 13 1962 (IDWR, 2015). In 2015 a curtailment order is under consideration where water rights junior to August 12 1973 are to be curtailed (IDWR 2015). For the purposes of illustration, in this study we chose January 1st, 1973 as the threshold priority date for curtailment.

curtailed in each zone. Distribution of curtailed acreages with water rights junior to January 1st 1973 across zones is presented in figure 3.

The model is applied in four steps as outlined in figure 4. Step one involves solving the model for a business as usual scenario with no water shortages. The purpose of this step is twofold. One is to validate model output in terms of its ability to simulate observed data. Table 1 presents results for a representative year with no water shortage curtailment. For each crop and county, maximum and minimum historically observed planted acreages are reported along side model simulated planted acreages. The results in table 1 confirm that the model does a reasonable job of simulating planted acreage in the region under business as usual conditions. Second purpose of step one is to obtain consumptive use per zone according to equation (10) under business as usual scenario ($CU_{z,\tau}^{BAU}$) with no water shortage.

In step 2 the model is solved with an additional constraint reflecting curtailment of acres with water rights junior to 1973 (equation 11). The results from this solution are used to estimate consumptive use per zone ($CU_{z,\tau}^{PAD}$), again using equation (10), under PAD-based curtailment with no water reallocation.

$$\sum_{c,s,it,ws} X_{c,z,s,it,ws,t} \leq Land73_z \qquad (11)$$

In step 3 the effects of the PAD-based curtailment on return flows at eleven reaches of the river are estimated using response functions. Equation 12 computes the return flow at each reach *k* at time *t* as a result of reducing consumptive water use due to curtailment relative to business as usual scenario across all zones and all periods preceding period *t*.

$$B_{k,t} = \sum_{z}\sum_{\tau}^{t}\left(CU_{z,\tau}^{BAU} - CU_{z,\tau}^{PAD}\right)\Psi_{z,k}\left(t-\tau\right) \qquad (12)$$

In step 4 the model is solved without curtailing acreages according to seniority of water rights. Instead, an additional constraint (13) is imposed which requires that the return flow in each of the *k* river reaches during the curtailment period cannot be less than what is produced by curtailing acres with water rights junior to 1973 without reallocation of water use.

$$\sum_{z}\sum_{\tau}^{t}\left(CU_{z,\tau}^{BAU}-\sum_{c,s,it,ws}X_{c,z,s,it,ws,\tau}*W_{c,z,s,it,ws,\tau}*IE_{c,z,s,it,ws,\tau}\right)\Psi_{z,k}\left(t-\tau\right)\geq B_{k,t} \qquad (13)$$

Results

Model results are obtained for water shortage scenarios where junior water users are curtailed for 1, 5, 10 or 20 years. In each of these scenarios the curtailment of junior water rights is enforced only for the duration of the curtailment order. After the curtailment order expires water use in each zone is only constrained by the total amount of adjudicated water rights held in the zone and other production constraints applicable in the business as usual scenario. Return flow requirement (13) is enforced only for the duration of the curtailment order. No additional return flow, beyond what is generated as a result of production under business as usual scenario, is required at any of the river reaches after the curtailment order expires. Figure 5 shows the effects of water use reallocation during PAD-based curtailment on current value regional profits over time. The vertical axis is the ratio of total current value regional profits from PAD-based curtailment with reallocation of water use and corresponding total current value regional profits from PAD-based curtailment with no water reallocation. In the one year curtailment scenario spatial reallocation of consumptive water use generates a 16% increase in regional profits in year one. In subsequent years the ratio is equal to one as spatial water use reverts back to business as usual solution with no curtailment. Similarly, the figure also shows analogous estimates for 5, 10, and 20 year curtailment scenarios. The scenario with reallocation of water use produces roughly 13 percent increase in annual agricultural profits. The results in each curtailment-length scenario show increased swings in profits during the last few years of the curtailment periods as the model attempts to take advantage of opportunities for water use reallocation in the final periods of the curtailment order with smaller implications for return flow requirements at the eleven river reaches post curtailment period.

Table 2 shows the distribution of change in profits across counties in the region by curtailment-length scenario. The counties in this table do not necessarily represent the actual county boundaries. For counties which do not fall within the ESP boundary only the proportion of the profits, corresponding to the share of the county falling within the ESP boundary, are reported. The table reports the ratios of current value county profits with and without water use reallocation under respective regulatory curtailment length scenario. For example, profits in Bingham county increase by 17 percent due to water use reallocation in a 1 year curtailment scenario. In a 5 year curtailment scenario cumulative profits during the 5 curtailment years increase by 16 percent and cumulative profits over 100 years increase by 1 percent. In a 1 year curtailment scenario all counties benefit from reallocation of water use, except for Bannock where total benefits are unaffected. Hence, at the county scale of analysis, water use transfers produce a Pareto Improvement relative to PAD-based curtailment of junior water rights in the one year curtailment scenario. In the longer term curtailment scenarios returns in Bannock and Jefferson counties decline while the profits in the rest of the counties increase. Hence, in these scenarios strictly Prior Appropriations-based curtailment with no water use transfers is Pareto Optimal. However, barring transaction costs and allowing for Kaldor-Hicks compensation

(Griffin 1995) the reallocation of water use after curtailing junior water users can produce a potentially Pareto dominant outcomes[6].

Figure 6 shows percent difference in total regional consumptive irrigation water use. The vertical axis shows the following ratio: $\left(CU^{PAD}_{Reallocation} - CU^{PAD}_{No\ reallocation}\right) \big/ CU^{PAD}_{No\ reallocation}$. Total regional consumptive water use in PAD-based curtailment with water use transfers in year one increases by more than 13 percent in a one year curtailment scenario relative to PAD-based curtailment with no water use transfers. Similarly, consumptive water use in other curtailment-length scenarios increases during the regulatory curtailment period. In subsequent years consumptive water use reverts to business as usual scenario as the region is no longer subject to curtailment orders and each production zone uses maximum available water subject to the volume of adjudicated water rights per zone similar to business as usual scenario.

The results show that relative to a strictly PAD-based distribution of water use with no reallocation, spatial transfers of water use decrease consumptive use in areas nearest to river reaches and increase water use in areas farther from the river. The results show a potential for reallocating water use such that return flows at eleven reaches of the river are unaffected. Disregarding transaction costs of such trades, or reallocations in water use, the results show a potential for enhancing economic benefits of water use from redistributing water use from low marginal value uses to relatively higher marginal value uses in response to PAD-based curtailment of junior users during water shortages.

The results also show that transfer of water use across time periods may facilitate optimal redistribution while avoiding third party externalities from spatial water transfers. Inter-temporal water trades can play a role in mitigating third party externalities in interconnected watersheds

[6] For a discussion of theoretical caveats relevant to the use of Pareto Optimality versus the use of potential Pareto Optimality as criteria for economic efficiency see Griffin (1995).

and have been institutionalized to some degree in some areas of the US (Brewer et al. 2008). Our solutions suggest that in the early stages of curtailment it may be optimal to significantly reduce water use in the areas which generate most return flow per unit of deposited water. This can allow areas which produce less return flow per unit of reduced CU to increase water use during the length of the curtailment relative to PAD-based curtailment distribution. The scenarios presented in figure 6 suggest that the longer the curtailment scenario, the lower the consumptive use in the first periods of the curtailment. Longer term curtailment orders, like ones similar to our 20 year curtailment scenario, imply more persistent requirements for return flows. In other words, short term return flow requirements are easier to fulfill than longer term flow requirements. For a 20 year curtailment scenario consumptive use in the region under PAD-based curtailment with reallocation in the first period falls below the corresponding consumptive use implied by PAD-based curtailment with no reallocation. This produces most "bang for the buck" in terms of return flows in subsequent periods and allows less connected areas to not have to decrease water use as much as what would have been implied by the PAD-based curtailment order. At the regional scale, consumptive use in the early periods in some areas is sacrificed for consumptive use in the later periods in other areas. Another reason for increasing regional CU over time during lengthy curtailment period is that increased water use in the later periods has smaller implications for return flows then increased water use in the earlier periods.

Elbakidze et al. (2012) use fixed irrigation efficiencies for sprinkler and flood irrigation technologies to compute spatial consumptive use proportional to the amount of water applied per acre. More accurate spatial representation of consumptive use can produce more accurate estimates of return flows from reductions in pumping. To examine the effect of alternative consumptive use computations, we solve the model assuming (a) fixed irrigation efficiency parameters similar to Elbakidze et al. (2012) where sprinkler and flood irrigation efficiencies are fixed at 0.7 and 0.65 respectively, and (b) variable irrigation efficiency parameters according to equations (9) and (10). Figure 7 compares the solutions from the two scenarios. The results for 10 and 20 years curtailment scenarios are presented for illustration purposes. Each curve shows the ratio of the difference in current value profits across solutions with fixed and variable irrigation efficiencies when reallocation of water is allowed, and corresponding profits under PAD-based curtailment with no reallocation of water use $\left[\pi^{\text{fixed irrig. eff.}}_{\text{with reallocation}} - \pi^{\text{var. irrig. efficiency}}_{\text{with reallocation}}\right] \Big/ \pi_{\text{no reallocation}}$. In this formulation profits under curtailment and no reallocation of water do not change depending on irrigation efficiency specification because implications for return flows are irrelevant for profits under PAD-based curtailment with no reallocation. However, estimates of return flows produced by PAD-based curtailment and no reallocation scenario change depending on irrigation efficiency specification and consumptive use across zones and over time. $\pi^{\text{fixed irrig. eff.}}_{\text{with reallocation}}$ and $\pi^{\text{var. irrig. efficiency}}_{\text{with reallocation}}$ are estimated subject to return flows produced in PAD-based curtailment with no reallocation (equation 13) computed assuming fixed and variable irrigation efficiency specifications respectively following step 3 in figure 4. The results indicate that the fixed irrigation efficiency specification produces inflated estimates of benefits from water reallocation. The disparity amounts to approximately 2 - 3% difference in the estimates of annual benefits. The estimates of the return flows from PAD-based curtailment with no reallocation of water use are greater when fixed irrigation efficiency is used then when variable irrigation efficiency is used[7]. Depending on the reach, the return flows from PAD-based curtailment with no reallocation are estimated to be 10 to 20 percent higher when fixed irrigation efficiency is used than when variable irrigation

[7] Estimates of the corresponding return flows per reach are available upon request.

efficiency is used. This means that the solution of the model with reallocation of water use is more heavily constrained - right hand side of equation (13) is greater - if fixed irrigation efficiency is used then when variable irrigation efficiency is used. In this respect profits under PAD-based curtailment with reallocation of water can be expected to be lower under fixed irrigation specification then under variable irrigation specification. However, consumptive use per zone under business as usual scenario is lower with variable irrigation efficiency specification than with fixed irrigation efficiency specification in every period. Hence, greater reductions in consumptive use are feasible when fixed irrigation efficiency specification is used than when variable irrigation specification is used. Greater $CU_{z,\tau}^{BAU}$ increases the feasible region of the choice variable in equation 13, and has a positive effect on the objective function value.

Conclusions

According to Howe et al. (1986), there are six criteria which determine if an exchange system may be a better distribution tool than PA: flexibility of allocation, security of tenure, consideration of opportunity costs, predictability of outcomes, perception of the process as fair, and reflection of public values. For an exchange mechanism to work, the public needs support it. A large step in this direction is to mitigate deleterious externalities. In this paper we present a model which explicitly restricts trade activities from generating externalities in the form of altered spatial and dynamic distribution of return flows.

We examine potential benefits in terms of increases in regional agricultural profits from reallocating water use after curtailment of junior water users in accordance with the Prior Appropriations doctrine. The reallocation is such that the total benefits of water use are maximized by ensuring that incremental water units are allocated to the users with highest marginal values. The reallocation is subject to a constraint that the return flows should be no less than the return flows generated by prior appropriations based curtailment with no reallocation. This model makes an important, although not exhaustive, attempt to model and internalize hydrologic externalities that arise when water use is spatially redistributed. The implicit assumption in this specification is that by controlling the effects on water flow along hydrologicaly predetermined river reaches, overall hydrologic externalities from water use reallocation in the region are minimized. The results quantify the benefits of reallocating water use relative to PAD-based distribution of water use during water shortages if institutional mechanisms and necessary technologies are in place to facilitate such water transfers. For a one year curtailment scenario total benefits increase by 16 percent relative to PAD-based curtailment. For longer curtailment scenarios annual benefits increase by approximately 13 percent annually.

The results illustrate the effect of the lengths of curtailment orders, which may be issued for shorter or longer term planning horizons. For example, in case of surface water shortage caused by lack of precipitation, junior water rights may be curtailed temporarily until sufficient surface water supplies accumulate. In case of ESPA, water shortages have taken the form of decreased return flows from the aquifer to the Eastern Snake River reaches (IDWR, 2014) as a result of declining groundwater levels (Cosgrove et al. 2008). Since the return flows along the river reaches are subject to spatially and temporally explicit hydro-connectivity, the mechanisms for augmenting or ensuring return flows need to explicitly consider the implications of inter-temporal water use. Our results show that during PAD-based curtailment with water use reallocation consumptive use can increase over time during the curtailment period relative to the consumptive use in PAD-based distribution of curtailment with no reallocation because water use in the later periods of curtailment is less constrained in terms of return flow requirements.

The estimates of the benefits from water use reallocation relative to PAD-based distribution in this study slightly differ from previous estimates obtained for this region (Elbakidze et al. 2012). On the one hand, addition of third party externality constraints likely reduces the benefits that could be obtained from reallocation of water use. However, several factors can affect the benefits from reallocation estimated in this study positively relative to Elbakidze et al (2012). First, in this model return flow requirements are only enforced for the duration of the curtailment order. No additional return flows beyond what is generated by production activities in the business as usual scenario are required after expiration of the curtailment order. Second, no lower bounds are placed on the planted acreages of crops. This allows for more flexibility in terms of planting decisions. Third, consumptive use is computed using endogenously determined irrigation efficiency rather than using two discrete values of irrigation efficiency for flood and sprinkler irrigation.

This analysis does not account for transaction costs associated with water use reallocation and trade, which arise due to legal complexities of water law and lack of appropriate institutional mechanisms. Although some mechanisms in Idaho, like ground water banking, are in place, reallocation of water use based on highest marginal value principle remains limited (Contor, 2010) at least in part due to high transaction costs. Third party externalities and associated regulatory requirements are major causes of high transaction costs limiting water trade (Brewer et al. 2008). In this study we describe a regional water reallocation model where third party externalities of water transfers are explicitly controlled. The model results are useful in terms of providing rough estimates of benefits from water use reallocation which can be compared to corresponding transaction costs when such estimates become available. Clearly, significant financial as well non-monetary costs can be involved with transactions arranging water use reallocation from low to high marginal value uses. Unfortunately, we lack quantitative data which would be appropriate for estimating such costs. While estimating transaction costs of water trade is outside the scope of the current paper, we recognize the important role of transaction costs for evaluation of water reallocation mechanisms (Hadjigeorgalis, 2009; Chong and Sunding, 2006). It is however, reassuring that small scale water markets in the form of regional water banks have been effectively utilized across western US including, but not limited to, Idaho (Contor, 2010).

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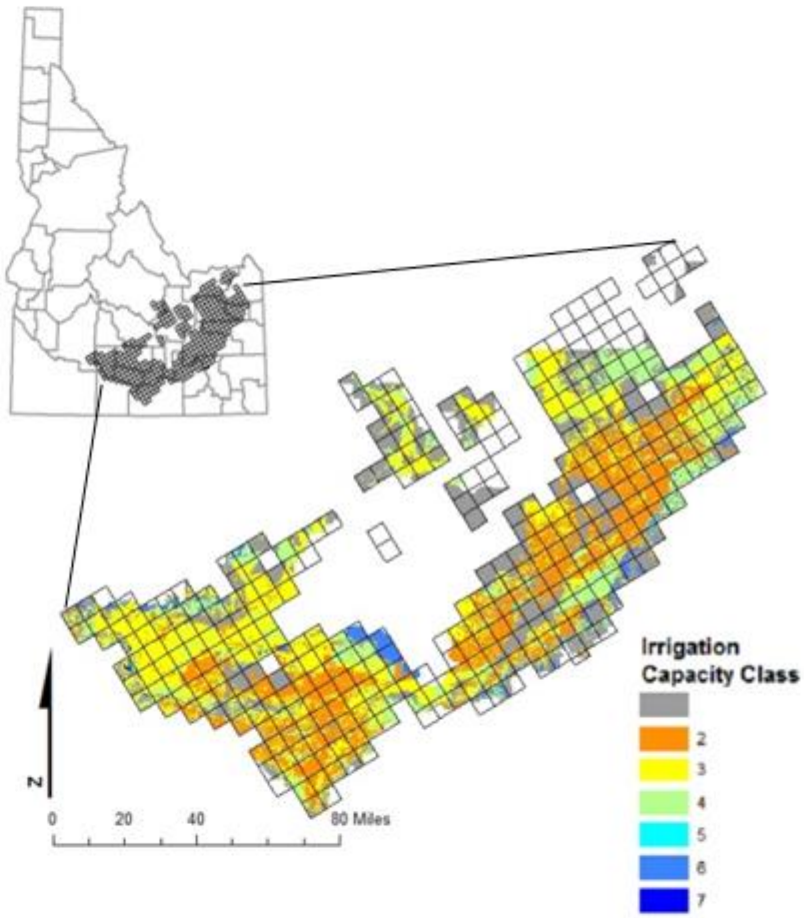

Figure 1. Eastern Snake River Plain and distribution of soil productivity classes

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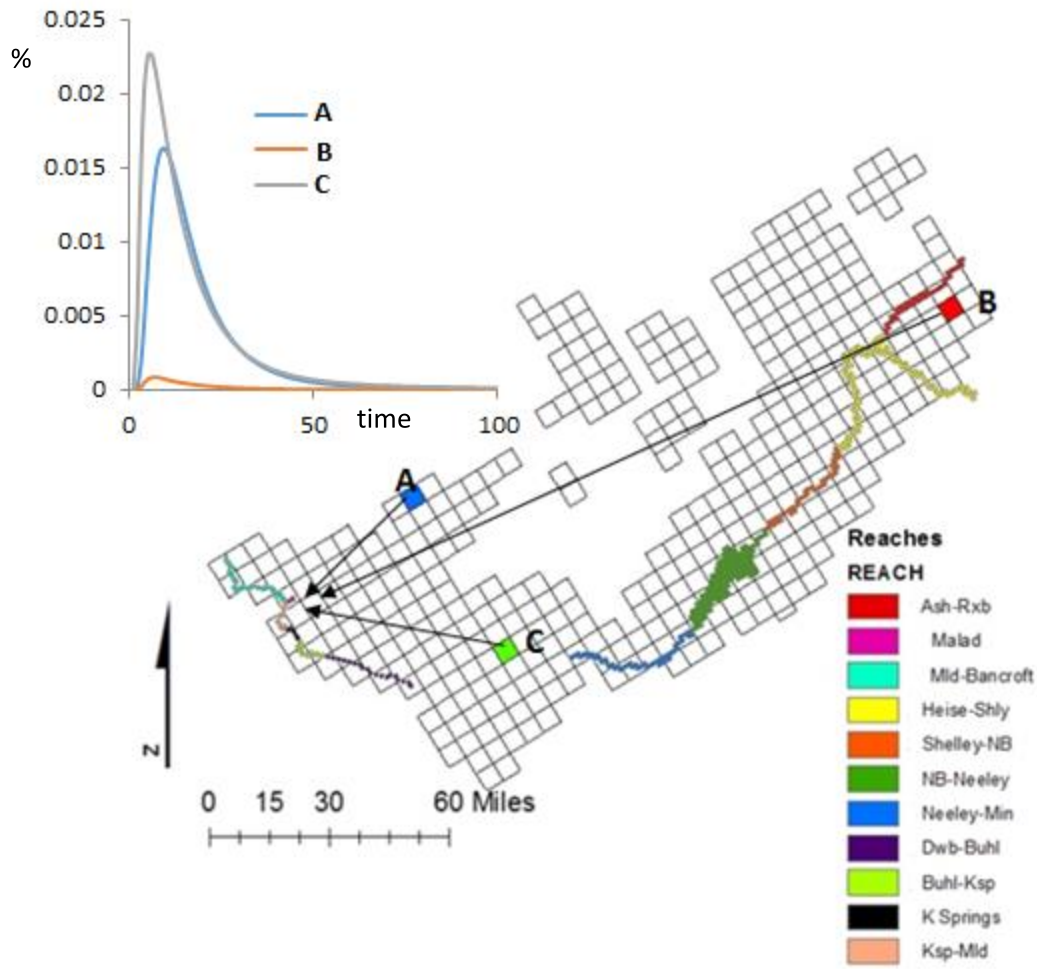

Figure 2. Response functions and eleven reaches of the Snake River.

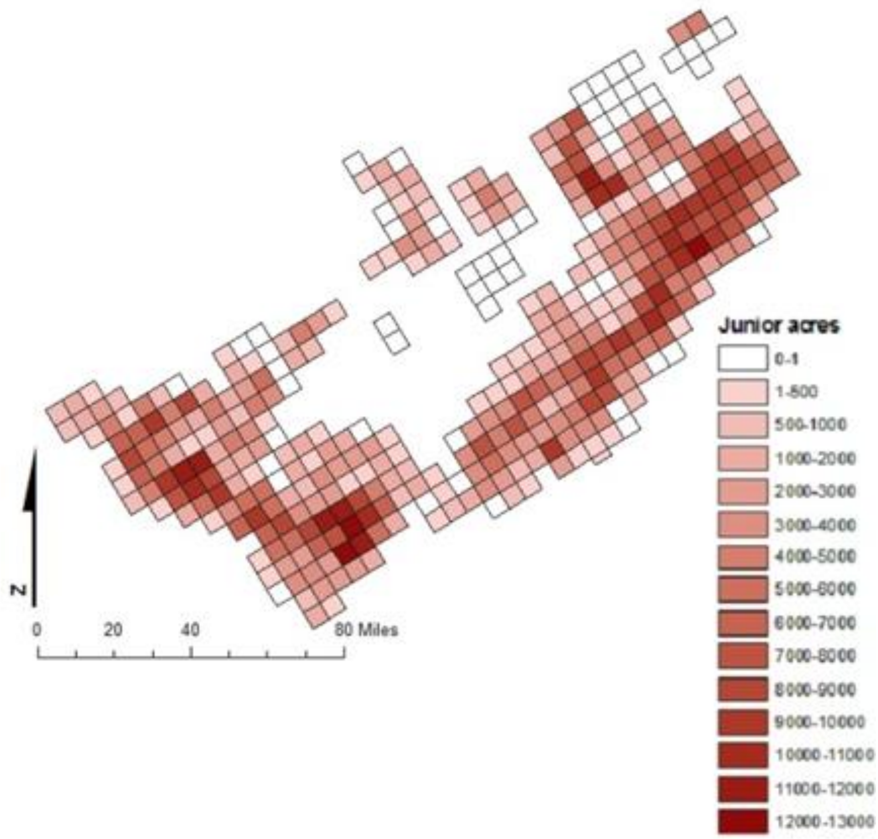

Figure 3 Spatial distribution of junior right acres

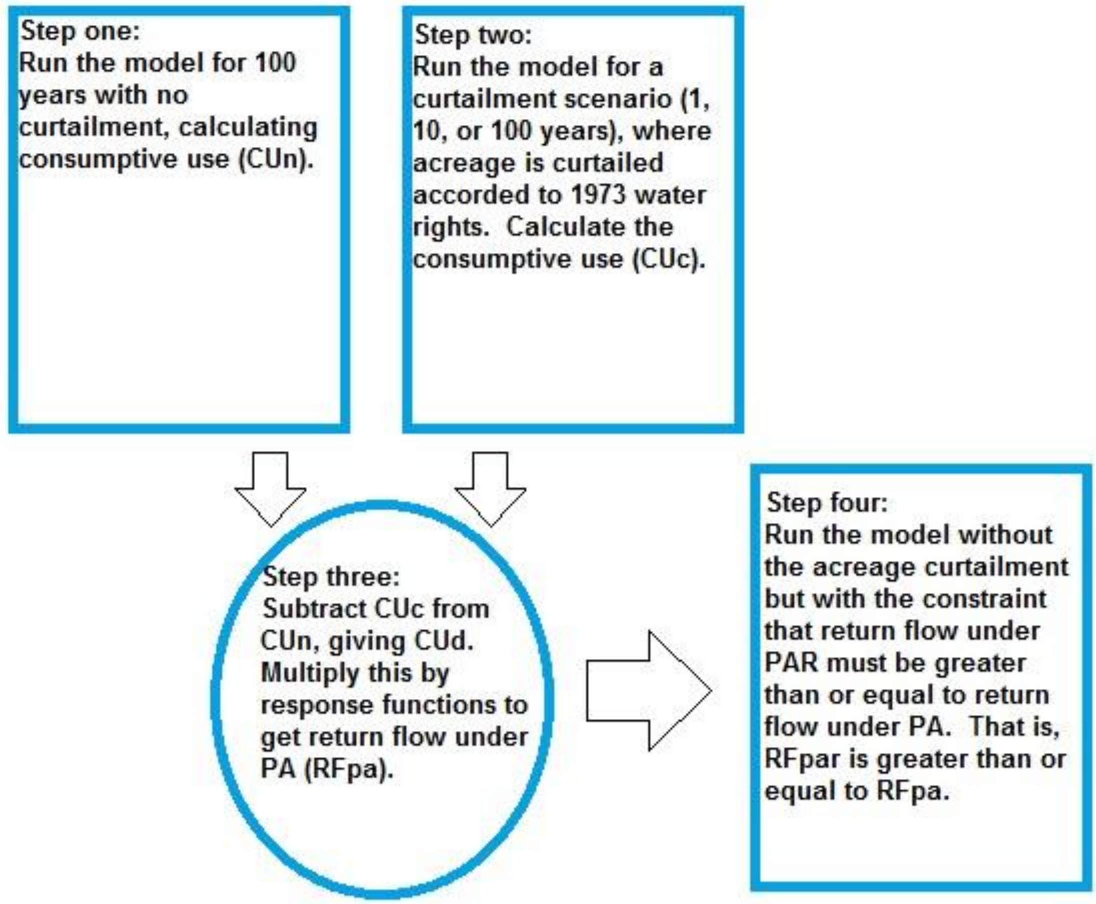

Figure 4. Structure of empirical policy analysis.

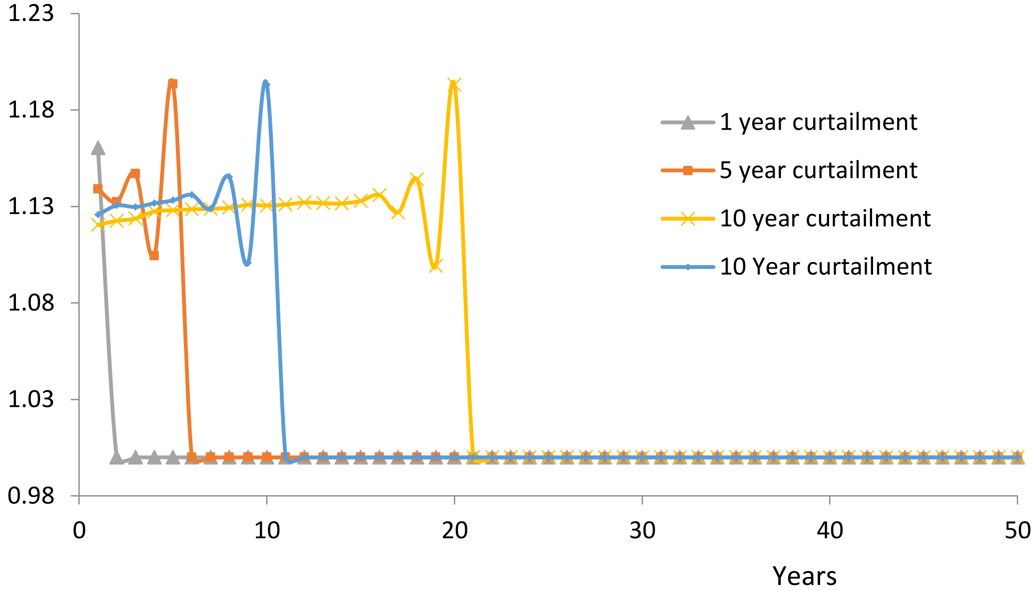

Figure 5. Ratio of current value regional profits (PA curtaiment with reallocation/PA curtailment with no reallocation)

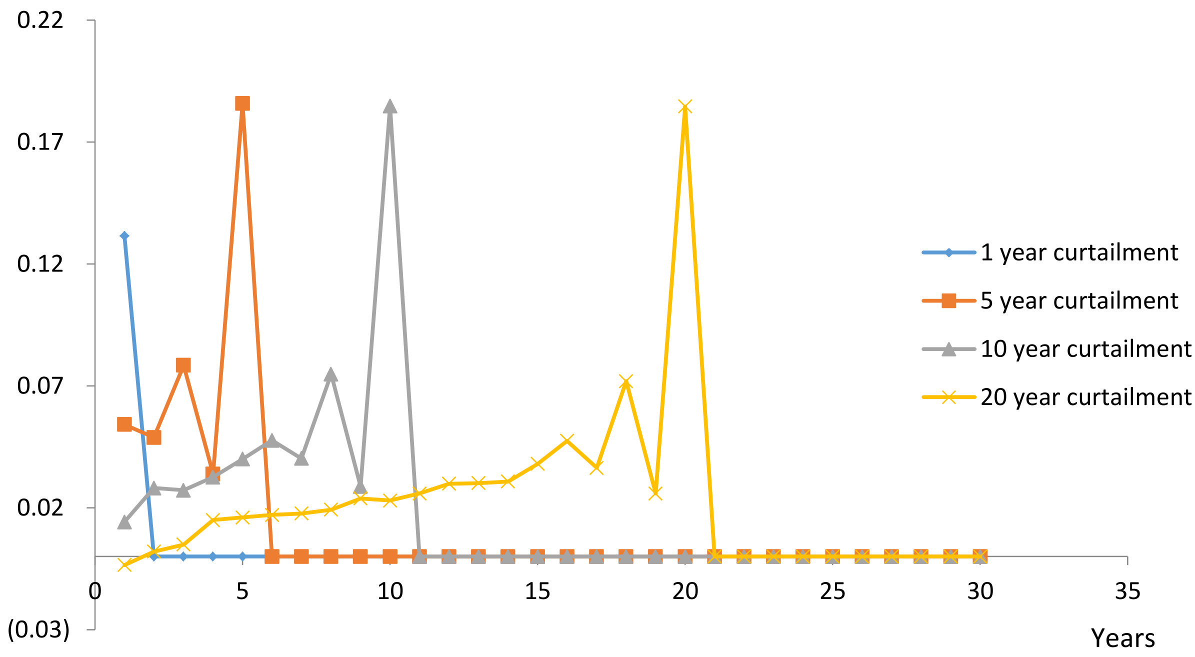

Figure 6. Percent difference in regional consumptive water use {(CU PA with reallocation-CU PA no reallocation)/CU PA no reallocation}

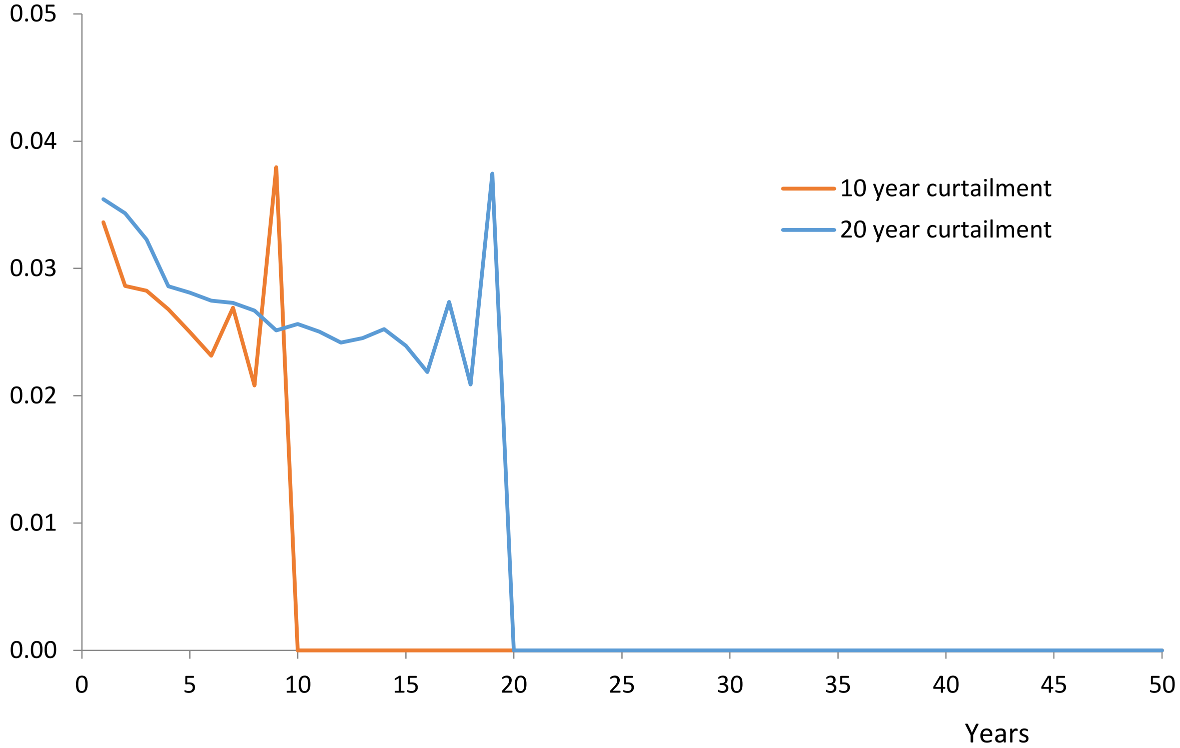

Figure 7 Difference in profit ratios: fixed irrigation efficiency minus variable irrigation efficiency

Sample Year	Bannock	Bingham	Blaine	Bonneville	Butte	Cassia	Clark	Fremont	Gooding	Jefferson	Jerome	Lincoln	Madison	Minidoka	Power
Alfalfa Min.	9,653	35,800	4,424	22,400	26,800	30,251	9,900	10,806	42,448	69,100	40,104	15,800	11,370	15,800	6,000
Alfalfa Planted	14,831	42,095	5,139	30,603	34,537	46,127	13,335	11,532	41,498	101,278	71,927	20,976	19,776	32,119	25,728
Alfalfa Max.	18,019	72,000	7,774	39,800	34,400	58,611	24,238	25,500	77,673	106,000	72,765	28,560	20,900	34,000	14,300
Barley Min.	2,092	14,200	3,025	34,800	9,700	20,448	-	25,600	10,616	38,400	16,423	3,500	29,900	29,100	-
Barley Planted	3,708	42,095	5,139	40,804	22,752	28,962	-	25,626	13,894	48,692	19,957	19,317	36,256	44,650	22,467
Barley Max.	28,477	66,000	7,904	103,000	27,800	57,613	17,700	90,100	41,364	106,000	44,309	21,000	74,500	45,700	48,300
Dry Beans Min.	-	-	-	-	-	5,705	-	-	7,742	-	4,938	-	-	3,300	-
Dry Beans Planted	-	-	-	-	-	7,542	-	-	10,351	-	9,978	-	-	8,030	469
Dry Beans Max.	-	-	-	-	-	15,348	-	-	31,111	-	36,443	1,680	-	10,900	900
Corn Grain Min.	-	-	-	-	-	537	-	-	4,066	-	2,299	-	-	-	-
Corn Grain Planted	-	-	-	-	-	1,234	-	-	4,601	-	1,271	-	-	-	-
Corn Grain Max.	-	400	-	2,100	-	4,781	-	-	17,911	500	11,510	2,400	-	5,800	3,800
Corn Silage Min.	-	-	-	-	-	553	-	-	5,211	-	3,628	1,300	-	-	-
Corn Silage Planted	-	-	-	-	-	6,308	-	-	9,201	-	8,707	13,420	-	-	-
Corn Silage Max.	-	3,700	-	5,800	-	21,090	-	-	50,727	6,800	44,933	10,920	1,800	6,000	700
Potato Min.	1,689	50,900	-	24,900	-	15,644	1,900	24,900	8,391	18,800	10,827	-	24,900	10,800	17,200
Potato Planted	3,708	78,315	682	40,804	-	21,420	9,002	25,626	13,802	38,953	9,978	4,608	36,256	28,590	16,414
Potato Max.	4,424	73,200	651	48,100	4,000	30,435	14,000	34,900	22,627	36,700	32,466	7,200	39,900	31,700	43,800
Sugar Beet Min.	-	5,900	-	-	-	14,435	-	-	2,506	-	6,699	3,100	-	29,100	6,200
Sugar Beet Planted	-	5,875	1,206	-	-	21,420	-	-	13,802	-	9,978	13,420	-	32,119	12,106
Sugar Beet Max.	-	25,200	878	-	-	30,500	-	-	13,479	-	22,081	11,160	-	51,500	15,700
Wheat Min.	5,229	96,300	-	21,400	-	30,918	3,800	7,100	12,611	25,500	17,594	4,700	20,500	20,100	30,100
Wheat Planted	7,415	156,630	682	40,804	11,376	41,873	4,333	7,688	13,802	38,953	51,970	18,028	36,256	52,679	28,989
Wheat Max.	12,227	156,400	1,659	91,400	14,000	101,606	24,600	47,700	44,732	72,500	62,414	24,360	44,800	68,200	162,000

Table 1: Crop Acreages in a non-curtailed year

	Curtailment Scenarios							
	1 Year		5 Years		10 Years		20 years	
Counties	Curtailment Period	100 years	Curtailment Period	100 years	Curtailment Period	100 years	Curtailment Period	100 years
BANNOCK	1.00	1.00	0.88	0.99	0.86	0.99	0.87	0.98
BINGHAM	1.17	1.00	1.16	1.01	1.17	1.01	1.17	1.03
BLAINE	1.06	1.00	1.06	1.00	1.06	1.01	1.06	1.01
BONNEVILLE	1.11	1.00	1.10	1.00	1.09	1.01	1.09	1.02
BUTTE	1.25	1.00	1.25	1.01	1.25	1.02	1.25	1.04
CASSIA	1.13	1.00	1.13	1.01	1.13	1.01	1.13	1.02
CLARK	2.18	1.00	2.12	1.03	2.03	1.05	1.98	1.10
FREMONT	1.47	1.00	1.45	1.02	1.46	1.03	1.46	1.07
GOODING	1.22	1.00	1.21	1.01	1.21	1.02	1.21	1.03
JEFFERSON	1.12	1.00	0.97	1.00	0.89	0.99	0.83	0.97
JEROME	1.07	1.00	1.06	1.00	1.06	1.01	1.05	1.01
LINCOLN	1.15	1.00	1.15	1.01	1.15	1.01	1.14	1.03
MADISON	1.19	1.00	1.19	1.01	1.20	1.02	1.20	1.03
MINIDOKA	1.09	1.00	1.08	1.00	1.07	1.01	1.05	1.01
POWER	1.14	1.00	1.10	1.00	1.06	1.00	1.06	1.01

Table 2. Ratios of current value county profits (PAD curtailment with reallocation/PAD curtailment with no reallocation)