Irrigation, Risk Aversion, and Water Rights under Water Supply Uncertainty

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Abstract
This article presents an economic model to examine optimal irrigated land allocation, water rights, and probability distribution of system risk in irrigation water supply. Results indicate that the allocative priority of water rights affects farmers' irrigation decisions and the skewness of the distribution of the system risk is the key parameter to determine this impact. The optimal acreage of irrigated land increases with the level of the allocative priority when the system risk features a negatively skewed distribution. A higher degree of negative skewness increases divergence in farm income between senior and junior water users and consequently increases the shadow value of the allocative priority.

Keywords: Water rights, skewness risk, water supply uncertainty, irrigated land allocation

1. Introduction

Water scarcity is among the top global risks that have drawn considerable attention from academic scholars and policymakers (WEF 2015). Adequate water supply is critical to successful agricultural production. In many parts of the world, sufficient water is difficult to access for a number of reasons. Water supply is highly uncertain and water storage and conveyance facilities are generally lacking in some places (Hanemann 2006). In other places, water resources often are poorly managed, leading to widespread inefficient use both physically and economically (Cai *et al*. 2003; Jensen *et al*. 1990; Schaible and Aillery 2012). Many strategies have been developed to improve the efficiency of water use and to enhance the adaptive capacity of rural-urban communities from the perspective of agricultural economics, hydrology, and institutional governance (Harou *et al.* 2009; Rosegrant and Binswanger 1994; Smit and Wandel 2006; Thompson 1993; Wada *et al.* 2014; among many). But it remains unclear how water scarcity and water supply uncertainty influence individual farmer's irrigation decisions and how institutional water sharing arrangements affect this decision-making process. This paper presents an economic model to address these issues.

Climatic factors have been long recognized as the major source of water supply uncertainty. Temperature and precipitation influence the timing and the volume of water flowing in river basins. In the U.S. West, for instance, irrigated agriculture relies on snowmelt-driven streamflow originated from high-elevation areas. A low-snow year can reduce the amount of water available for irrigation downstream. Earlier-than-normal spring snowmelt may cause the major April-July streamflow peak to occur one or more weeks earlier than usual. In both cases, spring and early summer river discharge declines (Cayan *et al.* 2001; Stewart *et al*. 2005). Beyond these causes of reduced water availability, global climate change has contributed to more frequent extreme weather events such as heat waves and persistent droughts in many places around the world in the recent decades, which further exacerbates water crises (Romero-Lankao *et al*. 2014).

The continuing debate over water markets highlights the importance and potential value of using water institutions to cope with increased water supply uncertainty. While being operated at the regional level, institutional water regimes can substantially affect individual farmers' responses to risk. Under the riparian doctrine in the U.S. East, for instance, each property owner fronting on a river has a right to unimpaired use of the waterway. Consequently, water resources are more like common property and water users share risks. In contrast, under the appropriative

doctrine of the U.S. West, the right to a certain amount of water is sorted in chronological order in which those rights were established. Water users with senior rights can use all the water before water users with junior rights have access to it (Hutchins 1968, 1977). Therefore, a given water supply shock affects senior and junior water users differently. Allocative priority allows senior water users to secure water supplies and to transfer the risk to junior water users. As a result, the system risk is redistributed unevenly among individual farmers, which subsequently affects their wellbeing. If a water shortage persists, the disparity of water distribution among water users may in turn bring unexpected changes to the governance regime.

The objective of this study is to explore the process of how a farmer makes irrigation decisions when water supply is uncertain, how institutional water governance such as water rights affects those decisions, and how those decisions subsequently influence the value of water rights. For this purpose, this paper develops a theoretical framework of a formal production model constrained by inadequate irrigation water supply. The model builds on the work of Feder (1980), who studied farmers' adoption of new technology under production uncertainty. We modify it to explicitly characterize institutional water governance and uncertainty in irrigation water supply; the latter allows us to differentiate individual risk from the system risk that is usually associated with events of global and regional climate change. In brief, irrigation water supply is stochastic, which presents a farmer with a problem of portfolio selection between risky and riskless activities. The farmer's optimal land allocation is therefore jointly determined by the probability distribution of the systemic water supply uncertainty, her individual water rights, and her attitude towards risk. To illustrate, we apply the theoretical model to the Eastern Snake River Plain Aquifer, the primary agricultural area in the state of Idaho where irrigation water diversion follows the prior appropriation doctrine.

By establishing a practically implementable framework, this paper makes four contributions to the literature. First, it explicitly models the institutional factors (or more precisely, the appropriative water rights) in water allocation from a farmer's perspective. While extensive literature is devoted to efficient water management from the perspective of water institutions (Fischhendler and Heikkila 2010; Rosegrant and Binswanger 1994; Saleth and Dina 2000; Saleth 2004; among many), there is relatively little work written from the farmer's perspective (Burness and Quirk 1979; Knox *et al*. 2012). The lack of micro-level data poses a challenge to empirically address this issue. The presented study not only conceptually analyzes how the allocative priority

of water rights affects a farmer's decisions related to irrigation water uncertainty, but also evaluates the shadow value of this priority in the empirical application. The implications drawn from both the theory and empirics can shed light on the cause of conflicts that occur in the process of water allocation.

Second, the paper discloses the importance of the skewness of the risk distribution to shaping a farmer's irrigation decisions. In the literature of risk relevant to production and climate (or weather), researchers often use the first and the second central moments to characterize uncertainty (for example, Deschênes and Greenstone 2007; Lobell *et al*. 2014; Mendelsohn *et al*. 1994), but the third moment that features the asymmetry of the risk probability distribution is generally overlooked, albeit with a few exceptions (Antle 1987; Kim *et al*. 2014; Weitzman 2009). This study demonstrates that the skewness of the risk distribution that entails severe water shortage is the key parameter determining the land allocation impact of water rights as well as the shadow value of the allocative priority of water rights.

Third, this paper explores the implication of equal sharing of the system risk in improving economic efficiency of water use. In a seminal paper, Burness and Quirk (1979) indicates that in theory, the unequal sharing of risk among water users leads to an inefficient use of water in the absence of a competitive market for the purchase and sale of water rights. The presented analysis empirically verifies this statement, although based on a conceptual model different from Burness and Quirk's (1979). The findings of this study can inform policymakers in designing institutional water sharing rules that aim at improving the efficiency of water allocation and at building resilience through risk management.

Fourth, the model, as presented in the next section, can be applied to a variety of topics involving risk-averse farmers and irrigation water supply uncertainties regionally and globally. The climate literature finds that risks related to changing temperatures and precipitation as well as snowmelt-driven water supply are closely connected as they are all consequences of climate change. In the context of risks that are caused by climate change, we stress that the presented model can be readily expanded to address the impact of uncertainties in climate change instead of in water supply. The ability to expand the model is particularly convenient in the absence of water supply data at the large geographic scale.

The remainder of this paper is organized as follows: Section 2 models the farmer's land use decisions in the presence of water scarce and uncertainty. Section 3 presents an application of the

model using data from Eastern Idaho and illustrates the major propositions. Section 4 concludes the paper.

2. The Model

To characterize irrigation water use in the arid climate zones where the risk of water shortage is present, this paper builds a framework of farmers' risk aversion analysis based on Feder (1980) and extended to model the impact of system risk on a farmer's water allotment given the farmer's priority in water allocation.

A competitive farmer is assumed to own a fixed-sized farm ($\bar{L}$) and to take prices as given. She allocates land between risky, water-intensive crops and riskless, drought tolerant crops.[1] For simplicity, we normalize the price of water-intensive crops and assume that drought tolerant crops have fixed returns per acre (R) and a constant returns to scale production technology such that the total output from water-intensive crops equals $L \cdot y(w)$, where L is the amount of irrigated land and w is water application rate per acre. By definition, $y' > 0$, $y'' < 0$, and $y(0) > 0$.

Compared with land resources, water resources are scarce and water constraint is binding. In practice, environmental, institutional, and economic factors impede market-based water trading; consequently, water transactions are rare (Hadjigeorgalis 2009) and are often associated with high transaction costs (Easter, Rosegrant, and Dinar 1999; Carey, Sunding, and Zilberman 2002). It is therefore reasonable to assume that water appropriation strictly follows the priority principle and that temporary market-based transactions such as water banking have an insignificant impact on regional water allocation. Assuming that a farm's total water allotment depends on the expected water allotments ($\bar{W}$), a standardized random variable ε with mean zero and variance one that measures the system risk of water supplies, and on a positive transform coefficient H that adjusts the impact of the system risk and reflects individual farmer's risk-bearing ability, the farmer's water constraint can be written as

$$wL = \bar{W} + \varepsilon H \geq 0, \tag{1}$$

[1] Admittedly, drought tolerant crops are subject to some damages caused by local stochastic weather. This risk is, however, sufficiently small compared with that in growing water-intensive crops. In addition, irrigated agriculture in many regions of the world relies more on snowmelt-driven streamflow originated from remote, high-elevation areas but less on local weather (e.g., the U.S. West and the mid and downstream areas in the Yangtze River and Yellow River basins of China). Therefore, even if there were small uncertainty in growing drought tolerant crops, the uncertainty is less likely to be correlated with the stochastic irrigation water supply, a major source of risk in growing water-intensive crops.

which implies $w = (\bar{W} + \varepsilon H)/L$. This setup allows explicitly integrating the institutional water sharing arrangement, as reflected by H. There is uncertainty in total water supply due to stochastic weather. This uncertainty has different impacts on farmers, depending on seniority of water right from a certain water source. Farmers who hold senior water rights or have ground water access are least affected by water supply uncertainty and thus have a high risk-bearing ability or a small H.

Assuming that the farmer's objective is to maximize the expected utility (U) of income (π), it is reasonable to characterize the utility function as strictly concave, reflecting risk aversion, i.e., $U = U(\pi)$, $U' > 0$, $U'' < 0$. We define income as the revenue from crop production

$$\pi \equiv L \cdot y(w) + R \cdot (\bar{L} - L). \tag{2}$$

The objective function is then given by

$$\max_L EU\left[L \cdot y\left(\frac{\bar{W}+\varepsilon H}{L}\right) + R \cdot (\bar{L} - L)\right]. \tag{3}$$

2.1 The Optimal Allocation of Land

The first order condition (FOC) of solving (3) can be derived as

$$\frac{\partial EU}{\partial L} = E\left[U' \cdot \left(y - R - y' \cdot \frac{\bar{W}+\varepsilon H}{L}\right)\right] = 0. \tag{4}$$

Denote $y - R - y' \cdot \frac{\bar{W}+\varepsilon H(V)}{L} \equiv \Phi$ (note that $\Phi = \partial\pi/\partial L$). Differentiating Φ with respect to (w.r.t.) L yields

$$\Phi_L \equiv \frac{\partial \Phi}{\partial L} = y'' \cdot \frac{[\bar{W}+\varepsilon H]^2}{L^3} < 0, \tag{5}$$

Since Φ is monotonically decreasing in L, an interior optimal solution for L is unique. If $\text{cov}(\Phi, U') = 0$, the optimal land allocation strategy is simply given by setting $\Phi = 0$. We posit, however, that $\text{cov}(\Phi, U') \neq 0$ holds under general situations, which directs the following discussions. From equation (4) one can derive the relationship between the optimal level of irrigation land and other parameters of the model.

Of particular interest are the effects of the transform coefficient on the optimal land allocation (dL^*/dH), which can be derived by differentiating equation (4) w.r.t. L and H:

$$\frac{dL^*}{dH} = -\frac{E\left(U'' \cdot y' \cdot \Phi \cdot \varepsilon + U' \cdot \Phi_H\right)}{E(U'' \cdot \Phi^2) + E(U' \cdot \Phi_L)}. \tag{6}$$

where $\Phi_H \equiv \frac{\partial \Phi}{\partial H} = -y'' \cdot \frac{\bar{W}+\varepsilon H}{L^2} \cdot \varepsilon$.

In order to determine the sign of dL^*/dH, we apply the Taylor series approximation to separate the random terms from the deterministic terms (see the appendix). The approximation implies that dL^*/dH will be negative if and only if

$$\gamma < \frac{y_0 - R - 3y_0'\bar{w}}{y_0''\bar{w}h}, \tag{7}$$

where $\gamma \equiv E(\varepsilon^3)$, measuring skewness of the probability distribution of the system risk ε (note that the variance of ε equals one); y_0, y_0', and y_0'' are *deterministic* terms evaluated at $\bar{w}$; $\bar{w} \equiv \bar{W}/L$; $h \equiv H/L$. Although the signs of both sides of condition (7) are undetermined, the inequality in (7) will always hold when γ is sufficiently small or R is sufficiently large.

This result yields the following proposition:

Proposition 1. *The optimal irrigated land (L^*) declines with the transform coefficient (H) if (i) the probability distribution of ε has a strong negative skew (left-tailed) or (ii) drought tolerant crops have high fixed returns per acre (R).*

The proofs of proposition 1 and all the subsequent propositions and corollaries are provided in the appendix.

Three points arise from this proposition. First, the effect of H on L^* remains indefinite in general. A negative effect is expected only if the aforementioned conditions meet. Second, when the shocks of severe water shortage are anticipated, a risk-averse farmer with a large H or a low risk-bearing ability will reduce L^*, and vice versa. Third, if R is sufficiently high, growing drought tolerant crops can serve as a risk-coping strategy to offset the disadvantage of farmers with a large H in the appropriation of regional water resources, leading to a decline in L^* of those farmers.

The level of the net returns from drought tolerant crops not only determines how H affects L^*, but also affects L^* itself. Differentiating equation (4) w.r.t. L and R yields:

$$\frac{dL^*}{dR} = -\frac{E\left(U''\cdot\Phi\cdot(\bar{L}-L)-U'\right)}{E(U''\cdot\Phi^2)+E(U'\cdot\Phi_L)}. \tag{8}$$

It is easy to show that $dL^*/dR < 0$. This result gives proposition 2:

Proposition 2. *The optimal irrigated land (L^*) decreases with higher returns per acre from drought tolerant crops (R).*

The intuition is straightforward. An increase in the profits of drought tolerant crops will always raise the comparative advantage of these crops relative to water-intensive crops whether

uncertainties exist in irrigation water supply or not. The revenue increase will consequently reduce the amount of land used for irrigation.

2.2 The Shadow Value of Allocative Priority of Water Rights

So far we have conceptually examined how a farmer's risk-bearing ability affects the optimal irrigated land allocation. As demonstrated, farmers with high risk-bearing capacity adapt easily to water supply uncertainties; they tend to devote more land to irrigation than average if planting water-intensive crops is more profitable. Therefore, high risk-bearing capacity is preferred. In this subsection, this capacity is connected to the allocative priority of irrigation water rights (V), an institutional factor under appropriation water sharing arrangement that is typical in many places including the Western United States. The shadow value of V is evaluated using the indirect utility function derived from the previous section. In the context of this study, the shadow value (λ) is defined as a farmer's willingness to pay for an extra unit of allocative priority.

Specifically, assuming that the transform coefficient H is a function of V, a large V is associated with a high risk-bearing ability or a small H, i.e., $H' \equiv \partial H/\partial V < 0$. The farmer's indirect utility function is given by:

$$U^*(V, \overline{W}, R) = EU\left[L^* \cdot y\left(\frac{\overline{W}+\varepsilon H(V)}{L^*}\right) + R \cdot (\overline{L} - L^*)\right], \tag{9}$$

The envelope theorem implies

$$\lambda = \frac{\partial U^*}{\partial V} = H'E(U'y'\varepsilon). \tag{10}$$

An analogue Taylor series approximation to equation (10) reveals that

$$\lambda \cong H'(U_0'y_0''h + U_0''y_0'HA), \tag{11}$$

where $A \equiv y_0'+y_0''h\,\gamma$. Since $H' < 0$, $H > 0$, $U_0'y_0'' < 0$, and $U_0''y_0' < 0$, λ is positive if (i) the term A is positive or (ii) A is negative and the magnitude of $U_0'y_0''HA$ is sufficiently small. Recall that γ measures the skewness of the distribution of the system risk ε. When $\gamma < 0$ is satisfied, ε has a left-tailed distribution, constituting a sufficient condition for a positive A and a subsequently positive λ.

Given $\gamma < 0$, it is easy to show that $\partial\lambda/\partial|\gamma| > 0$. The above discussion can be summarized as:

Corollary. *If the probability distribution of the system risk ε has a negative skew, at equilibrium the shadow value of the allocative priority of irrigation water rights (λ) increases with higher degree of the skewness of ε distribution to the left ($|\gamma|$).*

Intuitively, the shadow value relates to the potential negative impact that the system risk will bring to a farmer. This negative impact can arise from the severity of the system risk. The larger the negative impact, the more money a farmer is willing to pay in order to obtain an extra unit of allocative priority to hedge against risk.

3. An Application

To illustrate the model introduced in this work, this section presents a case study of irrigated agriculture in the Eastern Snake River Plain Aquifer (ESPA) in Southern Idaho. It starts by describing the background of the study area and the parameterization of the model. Then it analyzes the effects of transform coefficient on a farmer's irrigation decisions under various assumptions of uncertainty and calculates the shadow value of the allocative priority of water rights. Finally, the implications of equal sharing of system risk in improving water use efficiency and social benefits are explored.

3.1 Study Area

The ESPA is the prime agricultural region in Idaho. Located along the Snake River in the arid and semi-arid climate zones, irrigated agriculture is extensively practiced in this region. Irrigation accounts for approximately 80% of total water withdrawals for the 21 counties in the ESPA and the vicinity (Maupin *et al.* 2015). Therefore, the ESPA is highly dependent on adequate water supply during the growing season. According to Cropland Data Layers (CDL) from Cropscope through USDA, National Agricultural Statistics Service (NASS), farms grow a wide array of non-fruit crops, including alfalfa, barley, dry beans, corn, hay, lentils, oats, onions, peas, potatoes, sugar beets, and wheat (durum/spring/winter).

Like many parts of the U.S. West, the ESPA follows the prior appropriation doctrine to allocate water use under Idaho water rights (Bretsen and Hill 2009; Hutchins 1968 and 1977; Thompson 1993). Water rights are ranked based on the establishment date of individual water rights in ascending order (from 1870 to 2008 in our data sample). The ranking thus forms a ladder that sequences water sharing from the most senior to the most junior.

3.2 Simulation

The simulation practice is intended to explore the following questions:

1) Does there exist a threshold of the severity measure of the risk in water shortage, where a risk-averse farmer will decrease her land allocated to water-intensive crops with her transform coefficient on the one side but increase on the other side?
2) When the system risk remains unchanged, how does the allocative priority of water rights affect the farmer's optimal land allocation and the corresponding revenue?
3) What is the shadow value of the allocative priority of irrigation water rights? How does the value change with the partial effect of water rights priority on the transform coefficient, with the risk aversion coefficient, and with the skewness of the distribution of the system risk?

To address the first question, we generate a set of alternative risk scenarios in addition to the baseline by letting ξ varying from 0 to −2, measuring the severity of water crisis. For each given ξ, we draw a random sample of ε with the size of 10,000.[2] The new sample of ε features a system risk with the shape parameter that is different from the baseline level of −0.364. The representative farmer's optimization problem is solved by using the new sample, which yields a new optimal land allocation L^* each time. We calculate dL^*/dH using equation (6). To address the remaining two questions, we repeat the above procedure by changing the water rights priority index V, the coefficient of absolute risk aversion β, or the partial derivative of transform coefficient w.r.t. water rights priority H'. Then we estimate the expected optimal revenue using equation (2) and compute the shadow value of water rights using equation (11).

The Threshold of ξ

Figure 1 demonstrates the impact of the skewness of the system risk distribution on the partial derivative of the optimal land for irrigation w.r.t. the transform coefficient. The horizontal axis represents the shape parameter of the risk ξ and the vertical axis corresponds to the value of dL^*/dH. This curve can be used to explore the implications arising from proposition 1. Specifically, dL^*/dH monotonically increases with ξ while other parameters remain unchanged. As ξ lies around −0.272, dL^*/dH approaches 0, where changes in the transform coefficient will not affect the optimal land allocation. When ξ takes values smaller than −0.272, L^* declines with

[2] For the purpose of validation, we repeat generating ε for each given ξ and use them to calculate the optimal irrigated lands and the associated variables of interests. The simulation results are robust across the multiple trials.

H (see condition (7)). In particular, the risk is more unfavorable to farmers with larger H because these farmers will withdraw more land from irrigation. The baseline is one such case. This finding is consistent with proposition 1, implying that the shape of the system risk distribution is an essential parameter that determines how the transform coefficient influences the optimal irrigation land.

The Effects of Water Rights Priority

To address the question of how the allocative priority of water rights affects farmers' decisions about how much land they should irrigate, we consider three risk scenarios—ξ equals −0.364, −1.0, and −2.0, respectively. The first scenario corresponds to the baseline; the other two correspond to the scenarios where the system risk has moderate and extreme left-tailed distributions that are associated with more severe water losses. The simulation results are illustrated in Figure 2. Three points emerge from the figure. First, the optimal acreage of irrigated land increases with the level of water rights priority. When ξ equals −0.364, −1.0, and −2.0, the most junior water users ($V = 0$) will allocate 69.9%, 68.5%, and 62.3% of their lands for irrigation, whereas the most senior water users ($V = 1$) will allocate 70.1%, 69.5%, and 68.6% of their lands for irrigation.[3] The difference in land irrigation is equivalent to 1.2 acres, 9.8 acres, and 57.7 acres, respectively. Therefore, water rights does play a role in securing adequate irrigation water for farms.

Second, the importance of water rights to securing irrigation water relates to the skewness of the distribution of the system risk. Under the baseline where the skewness is close to zero, there is no significant difference in the irrigation decision between farmers with low priority and high priority in water allocation. The thin-tailed distribution of system risk explains, in part at least, why the difference in irrigation percentage between farms at the two extremes is small. As the distribution of system risk is more left skewed, the irrigation decision becomes more responsive to water rights priority. If the consequences of system risk become severe, senior water users will benefit significantly from a water sharing arrangement while junior water users will suffer major losses. This disparity leads to a substantive gap in farm income between these two groups. When $\xi = -2.0$, for instance, the expected annual revenue of farms with the most senior rights is around

[3] The impacts of the allocative priority of water rights are admittedly small under the baseline, partly because the average irrigation percentage is high in the study area, implying irrigation water is adequate to meet all rights in most years.

\$276.9 acre^{-1}, ~\$1.49 acre^{-1} higher than the expected annual revenue of farms with the most junior rights. The difference is equivalent to \$1,371 per annum for a representative farm. The climate literature indicates that global warming can result in frequent extreme heat events (droughts) and less water availability (Romero-Lankao *et al*. 2014). If water becomes less available, we may well expect that in the short term the difference in farm income between junior and senior water users will increase and in the long run will become considerably greater than it is now, and will eventually drive junior water users out of irrigated agriculture.

Third, our results accentuate the negative impact of potentially extreme water shortage on farmers' irrigation decisions. All else being equal, severe water shortages can decrease land allocated for irrigation. On average, the owner of a representative farm ($V = 0.44$) will withdraw 1.5% of land from irrigation under the risk setting of moderate extremity ($\xi = -1.0$). This decrease translates to a decline in the expected annual revenue of \$0.32 acre^{-1} or \$290 per farm compared to the baseline. Under a more extreme case of $\xi = -2.0$, a farmer will remove 6.5% of her land from irrigation, leading to a reduction of crop revenue by \$1.18 acre^{-1} or \$1,086 each year.

The Shadow Value of Water Rights Priority

Table 2 reports the shadow value of the allocative priority of water rights under different assumptions of the values of risk-relevant parameters—H', α, and ξ. In this table, columns 1–3 correspond to the combination of different parameter assumptions, column 4 corresponds to optimal irrigation percentage, and columns 5 and 6 correspond to the shadow value of the priority of water rights on a per-acre and per-farm basis, respectively. The price is the present lump sum value, evaluated with an assumed discount rate of 5% and an infinite time period.

As predicted by the theory, the shadow value increases with a larger partial effect of water rights priority on the transform coefficient, higher risk aversion, and larger magnitude of the left tail of the system risk distribution, which entails more severe water shortage. Under the baseline, the shadow value of a representative farm's allocative priority of water rights is about \$1.61 acre^{-1} or \$1,480 per farm. We discover that when H' declines from −0.39 from the baseline level to −0.49, the value of allocative priority increases by ~26%, implying that the priority becomes more valued among farmers if raising allocative priority can more effectively reduce the impact from the system risk. We also find that when α rises from the baseline level of 0.5 to 0.8, the shadow value only increases by ~2.4%, implying that changes in risk aversion have little impact

on the shadow value of allocative priority. This finding can also be used to test the sensitivity of the simulation to the assumption of the coefficient of risk aversion. Overall, the modeling results are robust to the alternative parameterization of α.

In contrast to H' and β, the impact on the shadow value resulting from changes in ξ is substantial. As ξ declines from the baseline level to −1.0, the shadow value of the allocative priority increases to \$10.04 acre^{-1} or \$9,230 per farm, six times as much as the value in the baseline. When the systemic risk of extreme water shortage is even higher ($\xi = -2.0$), the shadow value of the allocative priority is about \$44.62 acre^{-1} or \$41,000 each farm, 27 times more than the original value. This finding indicates that when the system risk is characterized by higher extremes, the value of allocative priority, albeit being at the same level, increases significantly. This result also offers an explanation of the cause of conflicts that occur in the process of water allocation. The allocative priority of water rights does not merely serve agricultural production; more important, it is increasingly recognized as real property. A higher value of senior priority in water allocation is therefore conveyed to the value aspects of water rights themselves and the land to which water rights are appurtenant.

3.3 The Implication of Equal Sharing of Risks

The analysis above reveals that the features of system risk and the allocative priority of water rights are important for a farmer to make irrigation decisions. This subsection explores the implications of equal sharing of system risk in improving water use efficiency. Intuitively, senior water users can divert more water for irrigation than the average water user, all else being equal. The extra amount of water that senior users withdraw, however, is less productive because of diminishing marginal productivity of water input and is less efficient because of diminishing marginal utility. On the other hand, junior users divert less water for irrigation than average. Water deficits result in large losses in farm revenue and farmers' welfare. This combined situation leads to inefficient water use.

Like in the preceding analyses, this subsection focuses on three risk scenarios—$\xi = -0.364$, −1.0, and −2.0. The 3,253 farms in the ESPA are assumed to have homogeneous production and utility functions. They differ only in their allocative priority of water rights, which are assigned based on the actual distribution of water rights in the sample (Figure 3). This simplified assumption allows us to identify changes in social benefits by comparing the factual and counterfactual situations in terms of the risk sharing arrangement. Under each risk scenario, we

solve every farm's optimization problem and calculate the total expected revenue in the region. Equal sharing of system risk presumes that all of the farmers have the same allocative priority of water rights, which implies equal sharing of water ($V = 0.44$). In this counterfactual experiment, the optimal irrigation percentage is therefore approximately 70% for each farm. We compare the expected annual revenues and the lump sum values in the ESPA before and after equalizing risks among farms. The results are reported in Table 3.

Results indicate that with the factual water sharing arrangement and the skewness of the system risk distribution at the baseline level ($\xi = -0.364$), the expected annual crop revenue in the ESPA is approximately $829 million, equivalent to a lump sum value of $16,581 million if a discount rate of 5% and an infinite time period are assumed. Equalizing the allocative priority of water rights increases the expected revenue. The more severe the consequence resulting from the system risk, the more benefits the equal sharing of risk will bring. Under the system risk at the baseline level, for instance, the new water allocation arrangement will increase the expected revenue by $2,680 per annum or of $53,600 in total. When the system risk has a moderate left-tailed distribution ($\xi = -1.0$), the increment of revenue can reach $3,690 per annum, equivalent to a lump sum value of $73,800. When ξ decreases to -2.0, the change widens to $47,040 per annum or $940,800 in total, 17 times more than the baseline level.

The finding in this paper empirically verifies Burness and Quirk's (1979) argument about inefficient water use caused by unequal sharing of risks among water users. We find that the magnitude of this inefficiency is associated with the severity of water shortage risk from extreme events. When the system risk is more likely to induce serious consequence such as persistent drought, senior water users can have a greater advantage in allocating regional water resources than their junior counterparts. This inequality, however, distorts the allocation of water resources at the regional level, where social benefits could be higher. The more left skewed the system risk, the more the degree of the distortion reduces the value of water use and consequently increases the need and benefits for water rights rearrangement. Thus, a proper assessment of the systemic risk in irrigation water supply is crucial to water agencies in determining whether or not to carry out such policies.

4. Conclusions

This paper explores the impacts of the allocative priority of water rights as an indicator of farmers' risk-bearing ability on irrigated land allocation under different assumptions of system risk in irrigation water supply. A theoretical model is developed and applied in a case study of the ESPA in Idaho. The paper reaches several conclusions. First, the allocative priority of water rights affects farmers' irrigation decisions. The skewness of the distribution of system risk is the key parameter to determine the land allocation impact of the allocative priority. Results reveal that the optimal acreage of irrigated land increases with the level of water right priority when the system risk features a left-tailed distribution that entails severe water shortage.

Second, a higher degree of negative skewness of system risk distribution increases the shadow value of the allocative priority of water rights. Results from the case study indicate that when the shape parameter of the risk distribution declines from the baseline level of −0.364 to a more extreme case of −2.0, the shadow value of the allocative priority of a representative farm will increase from $1,480 to $41,000 (27 times more than the original value). This finding helps explain why farmers are increasingly recognizing water rights as real property given the consensus that global climate change can cause frequent extreme drought events, leading to intensified water crises.

Moreover, while it can help individual farmers to hedge against the system risk in the water supply, the appropriative water sharing rule has drawbacks. In fact, this doctrine induces unequal sharing of risks among water users and creates economic inefficiency. Our results reveal that the associated economic losses are estimated in the range of $2,680–$47,040 per annum or $53,600–$940,800 in total in the ESPA. Importantly, the deadweight loss increases with the severity of the water shortage risk, which, in turn, strengthens the argument that the country (or states) should revamp existing institutional water governance (Thompson 1993; Rosegrant and Binswanger 1994; Narain 2000; Efltelson 2005). System risk plays a key role in influencing decision-making about agricultural land use at both micro and macro levels and therefore should be further explored in both climatology and hydrology studies as well as in related social sciences.

References

Antle, J.M. 1987. Econometric estimation of producers' risk attitudes. *American Journal of Agricultural Economics* 69(3): 509–522.

Bretsen, S.N., P.J. Hill. 2009. Water markets as a tragedy of the anticommons. *William & Mary Environmental Law and Policy Review* 33(3): 723–783.

Burness, Stuart H., James P. Quirk. 1979. Appropriative water rights and the efficient allocation of resources. *The American Economic Review*, 69(1): 25–37.

Cai, Ximing, Mark W. Rosegrant, Claudia Ringler. 2003. Physical and economic efficiency of water use in the river basin: Implications for efficient water management. *Water Resources Research*, 39(1): 1013.

Cayan, S., A. Kammerdiener, M.D. Dettinger, J.M. Caprio, D.H. Peterson. 2001. Changes in the onset of spring in the Western United States, *Bulletin of American Meteorology Society* 82(3): 399–415.

Deschênes, O., M. Greenstone. 2007. The economic impacts of climate change: Evidence from agricultural output and random fluctuations in weather. *The American Economic Review* 97(1): 354–385.

Easter, K.W., M.W. Rosegrant, A. Dinar (eds.). 1998. *Markets for Water: Potential and Performance*. Boston: Kluwer Academic Publishers.

Feder, Gershon. 1980. Farm size, risk aversion and the adoption of new technology under uncertainty. *Oxford Economic Papers* 32(2): 263–283.

Feitelson, E. 2005. Political economic of groundwater exploitation: The Israeli case. *Water Resources Development* 31(3): 413–423.

Fischhendler, I., T. Heikkila. 2010. Does integrated water resources management support institutional change? The case of water policy reform in Israel. *Ecology and Society* 15(1): 4.

Frija, I., A. Frija, A. Chebil, H.C. M'Hamed, S. Speelman, M. Makhlouf. 2014. Marginal water productivity of irrigated durum wheat in semi-arid Tunisia. *Journal of Agricultural Science* 6(10): 84–95.

Frisvold, G.B., K. Konyar. 2012. Less water: How will agriculture in Southern Mountain states adapt? *Water Resources Research* 48.

Hanemann, W.M. 2006. The economic conception of water, in Peter P. Rogers, M. Ramon Llamas and Luis Martinez-Cortina (eds.), *Water Crisis: Myth or Reality?* NewYork: Taylor & Francis, pp. 61–91.

Harou, J.J., Pulido-Velazquez, M., Rosenberg, D.E., Medellín-Azuara, J., Lund, J. R., Howitt, R. E. 2009. Hydro-economic models: Concepts, design, applications, and future prospects. *Journal of Hydrology* 375(3): 627–643.

Hutchins W.A. 1968. The Idaho Law of Water Rights. *Idaho Law Review* 5(1): 1–129.

Hutchins W.A. 1977. *Water Rights Laws in the Nineteen Western States*, Vol. III. Natural Resource Economics Division, Economic Research Service, U.S. Department of Agriculture, Washington, D.C.

Idaho Department of Water Resources, Land Cover and Vegetation, Eastern Snake River Plain Irrigated Land, http://www.idwr.idaho.gov/GeographicInfo/gisdata/land_cover.htm, (Last accessed July 8, 2014)

Idaho Department of Water Resources, 2006 Irrigated Land Classification for the Eastern Snake Plain Aquifer, http://www.idwr.idaho.gov/News/WaterCalls/Surface%20Coalition%20Call/background/irri

gated-nonirrigated%20by%20county/2006%20irrigated-nonirrigated%20classification%20report.pdf, (Last accessed July 8, 2014)

Idaho Department of Water Resources, Water Rights Layers, http://www.idwr.idaho.gov/GeographicInfo/gisdata/water_rights.htm, ((Last accessed February 1, 2011)

Jensen, M. E., W. R. Rangeley, P. J. Dielerman. 1990. Irrigation trends in world agriculture, in *Irrigation of Agricultural Crops*, Agron. Monogr. Ser., 30, edited by B. A. Stewart, and D. R. Nielsen, pp. 31–67, American Society of Agronomy, Madison, WI.

Kim, K., J.-P. Chavas, B. Barham, J. Foltz. 2014. Rice, irrigation and downside risk: a quantile analysis of risk exposure and mitigation on Korean farms. *European Review of Agricultural Economics* 41(5): 775–815.

Knox, J.W., M.G. Kay, E.K. Weatherhead. 2012. Water regulation, crop production, and agricultural water management—Understanding farmer perspectives on irrigation efficiency. Agricultural. *Water Management* 105: 3–8.

Lobell, D.B., M.J. Roberts, W. Schlenker, N. Braun, B.B. Little, R.M. Rejesus, G.L. Hammer. 2014. Greater sensitivity to drought accompanies maize yield increase in the U.S. Midwest. *Science* 344(6183): 516–519.

Maupin, M.A., Kenny, J.F., Hutson, S.S., Lovelace, J.K., Barber, N.L., and Linsey, K.S. 2014, Estimated use of water in the United States in 2010: U.S. Geological Survey Circular 1405, 56 p., http://dx.doi.org/10.3133/cir1405.

Mendelsohn, R., W.D. Nordhaus, D. Shaw. 1994. The impact of global warming on agricultural: A Ricardian analysis. *The American Economic Review* 97(1): 753–771.

Moore, M.R., N.R. Gollehon, D.H. Negri. 1993. Alternative forms for production functions of water-intensive crops. *The Journal of Agricultural Economics Research* 44(3): 16–32.

Narain, V. 2000. India's water crisis: the challenges of governance. *Water Policy* 2(6): 433–444.

Romero-Lankao, P., J.B. Smith, D.J. Davidson, N.S. Diffenbaugh, P.L. Kinney, P. Kirshen, P. Kovacs, and L. Villers Ruiz. 2014: North America. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1439–1498.

Rosegrant, M.W., H.P. Binswanger. 1994. Markets in tradable water rights: potential for efficiency gains in developing country water resource allocation. *World Development* 22(11): 1613–1625.

Saleth, M.R. 2004. Strategic analysis of water institutions in India: Application of a new research paradigm. Research Report 79. Colombo, Sri Lanka: International Water Management Institute.

Saleth, M.R. and A. Dina, 2000. Institutional changes in global water sector: trends, patterns, and implications. Water Policy 2: 175–199.

Schaible, G. D., and M. P. Aillery. 2012. Water Conservation in Irrigated Agriculture: Trends and Challenges in the Face of Emerging Demands, EIB-99, U.S. Department of Agriculture, Economic Research Service. Washington, D.C.

Smit, B., J. Wandel. 2006. Adaptation, adaptive capacity and vulnerability. *Global Environmental Change* 16(3): 282–292.

Stewart, I.T., D.R. Cayan, M.D. Dettinger. 2005. Changes towards earlier streamflow timing across Western North America. *Journal of Climate* 18(8): 1136–1155.

Thompson, Barton H. Jr. 1993. Institutional perspective on water policy and markets. *California Law Review* 81(3): 671–764.

U.S. Department of Interior, Bureau of Reclamation, Pacific Northwest Region, AgriMet, Crop Water Use Information http://www.usbr.gov/pn/agrimet/h2ouse.html, (last accessed February 2014)

U.S. Department of Agriculture, National Agricultural Statistics Services, Quick Stats of Crops and Vegetables Price Received and Yield for 2003–2007, http://quickstats.nass.usda.gov/, (Last accessed May 10, 2014)

U.S. Department of Agriculture, National Agricultural Statistics Services, Cropland Data Layer (CDL) for 2008–2010, http://datagateway.nrcs.usda.gov/, (Last accessed August 1, 2012)

U.S. Department of Agriculture, Natural Resources Conservation Services, U.S. General Soil Map (STATSGO2), http://soildatamart.nrcs.usda.gov/, (Last accessed August 1, 2012)

Wada, Y., T. Gleeson, L. Esnault. 2014. Wedge approach to water stress. *Nature Geoscience* 7(9): 615–617.

Weitzman, M.L. 2009. On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics* 91(1): 1–19.

World Economic Forum (WEF), 2015, Global Risks 2015, 10th Edition, Geneva, Switzerland, http://www.weforum.org/reports/global-risks-report-2015, (Last accessed November 8, 2015)

Xu, W., L.E. Scott, A.M. Richard. 2014. Climate change, water rights, and water supply: The case of irrigated agriculture in Idaho. *Water Resources Research*. DOI: 10.1002/2013WR014696.

Figures

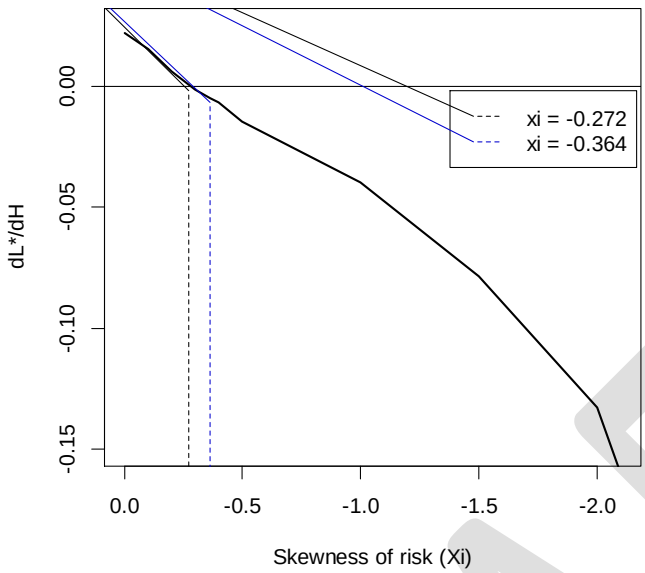

Figure 1. The partial effect of water allotment coefficient on optimal level of irrigated land versus skewness of risk

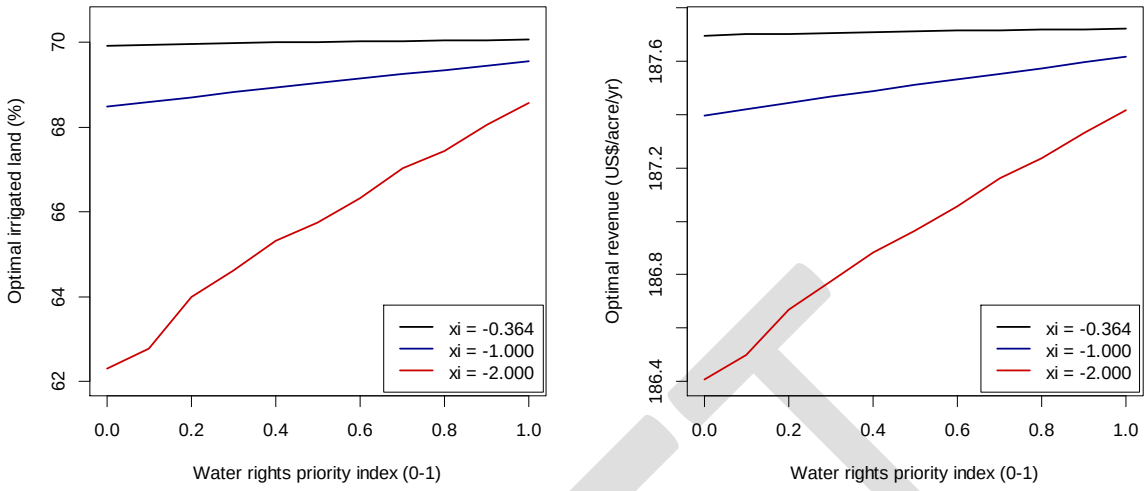

Figure 2. The effects of water rights priority under different assumptions of skewness of risk

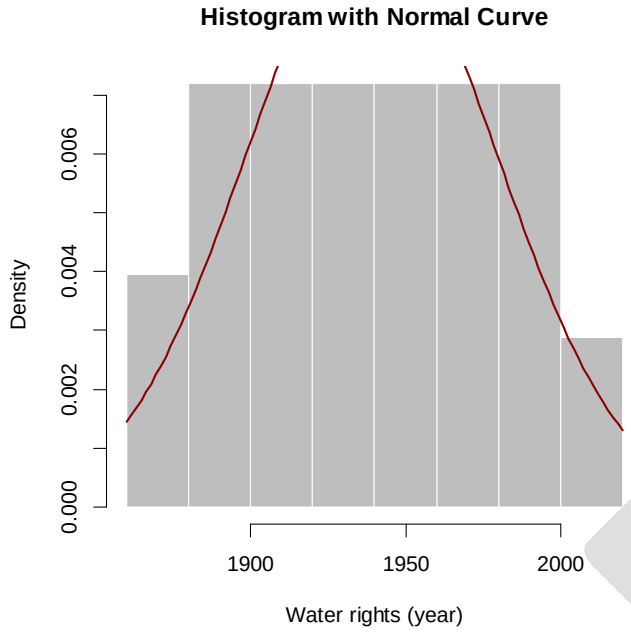

Figure 3: Histogram of farmers' water rights in the ESPA

Tables

Table 1. Characteristics of land and water use, production, and utility

Parameters	Symbols	Values	Notes
Land & water use			
Average irrigated land	L	643	Measured by acres, calculated from sample
Average farm size	$\bar{L}$	919	Measured by acres, calculated from sample
Normalized annual revenue from drought tolerant crops	R	3.01	Measured by thousand lb acre^{-1}, representing the annual returns to drought tolerant crops normalized by the price index of water-intensive crops
Average farm-level water allotment	$\bar{w}$	2.7084	Measured by feet per annual, calculated from sample
System risk of water supplies			
Location parameter	μ	−0.095	Estimated from sample
Scale parameter	σ	0.313	Estimated from sample
Shape parameter	ξ	−0.364	Estimated from sample
Allocative priority			
Average allocative priority index	V	0.44	Calculated from sample (0−1)
Priority function parameters—intercept		0.0000	Estimated from the *H(V)* equation
Priority function parameters—risk response	a	0.6027	Estimated from the *H(V)* equation
Priority function parameters—risk* priority response	H'	−0.3866	Estimated from the *H(V)* equation
Production function			
Preference (output elasticity) of water input	ρ	0.107	Estimated from the production function of water-intensive crops
Scalar	b	3.0238	Estimated from FOC
Utility function			
Arrow-Pratt measure of relative risk aversion (Base Case)	α	0.50	Set as in Feder (1980)

Table 2. Shadow value of the allocative priority of water rights under different assumptions of risk parameters

Skewness of system risk	Risk aversion coefficient	Partial effect of water rights priority on water supply variation	Optimal irrigated land (%)	Shadow value of allocative priority of water rights: Acre-based value (US$/acre)		Shadow value of allocative priority of water rights: Farm-based value (US$1,000)	
(1)	(2)	(3)	(4)	(5)		(6)	
-0.364	0.5	-0.39	70.00	1.61	(1.34–2.01)	1.48	(1.23–1.85)
-0.364	0.5	-0.49	69.93	2.02	(1.69–2.53)	1.86	(1.55–2.32)
-0.364	0.8	-0.39	69.92	1.65	(1.37–2.06)	1.51	(1.26–1.89)
-1.000	0.5	-0.39	68.48	10.04	(8.37–12.55)	9.23	(7.69–11.54)
-1.000	0.5	-0.49	68.48	12.64	(10.53–15.80)	11.62	(9.68–14.52)
-1.000	0.8	-0.39	68.47	10.10	(8.41–12.62)	9.28	(7.73–11.60)
-2.000	0.5	-0.39	62.30	44.62	(37.18–55.77)	41.00	(34.17–51.26)
-2.000	0.5	-0.49	62.30	56.16	(46.80–70.20)	51.61	(43.01–64.51)
-2.000	0.8	-0.39	61.16	45.32	(37.76–56.65)	41.65	(34.71–52.06)

Note: Columns 5 and 6 correspond to the present value of the shadow value of the allocative priority of water rights. We assume a 5% (±1% in parentheses) of discount rate per annum and an infinite time period.

Table 3. The impact of equal sharing of the system risk in the ESPA

	Before equal sharing of risk			Changes attributed to equal sharing of risk		
Skewness of system risk	Expected annual revenue (million US$)	Present lump sum value of the expected revenue (million US$)		Expected annual revenue (US$1,000)	Present lump sum value of the expected revenue (US$1,000)	
(1)	(2)	(3)		(4)	(5)	
-0.364	829.1	16,581	(13,818–20,726)	2.68	53.6	(44.7–67.0)
-1.000	828.1	16,562	(13,802–20,703)	3.69	73.8	(61.5–92.2)
-2.000	825.5	16,510	(13,758–20,637)	47.04	940.8	(748.0–1166.0)

Note: There are 3,253 farms in the study area. Columns 3 and 5 correspond to the present value of the expected revenue in the ESPA. We assume a 5% (±1% in parentheses) of discount rate per annum and an infinite time period.