# Water and Growth in an Agricultural Economy

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## Abstract

Although water markets have been proposed as a possible solution to growing conflicts over water, between agriculture and other uses, farmers with prior appropriation rights are often unwilling to "trade" water rights even if they have excess available water to sell. The purpose of the following paper is to explain the economic behavior that underlies this reluctance of farmers to engage in water markets. We model the relationship between water and growth in the agricultural economy through the perspective of a representative agricultural household that engages in irrigated farming as its principal economic activity. Given prior appropriation, water is treated as a private good, but the household faces increasing costs in appropriating and using more water, $r$, from its fixed water right, $w$. Under conditions of excess available water, the agricultural household can attain a long-run saddle point steady state, and if capital and water are not highly substitutable (the most likely case), water use will rise as the household accumulates capital and increases consumption. However, under conditions of a binding water constraint, per capita consumption (and thus welfare) must always be declining. The implication of this analysis is that the agricultural household clearly wants to maintain a situation of excess water supply, as the farming household would be reluctant to sell off "excess water" because of the possibility that this might drive the household into a situation where all available water must be appropriated.

**Keywords:** agricultural economy, prior appropriation, water, water rights, water scarcity.

## 1. Introduction

Water is an important input into agricultural production, and competing inter-sectoral demands for limited availability for water often result in growing pressure on farmers to give up their water rights for more highly valued urban and municipal uses. This is particularly true in the Western United States, where semi-arid climate and periodic drought increase the physical scarcity of water, and historically, the "doctrine of prior appropriation" has ensured that irrigated agriculture has obtained first rights to much surface and groundwater.[1] Wyoming is a good example, as in this state 80-85 percent of freshwater consumption is for irrigated agriculture, yet there is an increasing water demand for municipal and industrial uses (Jacobs and Brosz 2000). Across all Western states, agricultural irrigation accounted for 95 percent of total consumptive water use in 1960, and 92 percent in 1995 (Gollehon 1999).

Water markets have been proposed as a possible solution to growing conflicts over water, between agriculture and other uses (Anderson and Hill 1997; Dosi and Easter 2003; Easter and Rosegrant 1998; Haddad 2000; NRC 1992). However, substantial obstacles remain to the rapid spread of water markets, despite the large potential gains from trade between agricultural and other uses of water.[2] Most explanations of the resistance to rural-to-urban water exchanges have focused on the problem of transaction costs, which usually arise through incomplete property rights, externalities, institutional and regulatory rigidities, and uncertainty over climate and drought conditions (Colby 1995; Libecap 1999). But studies of Western water markets suggest that transaction costs arising from state policies and regulations are not excessive, and may even be a reasonable means to "internalize" some of the social costs associated with such transfers (Colby 1995).

Transactions costs arising from institutional rigidities, policies and regulations may therefore not be as substantial an obstacle to the development of water markets as previously thought. Instead, the more recent focus has been on other explanations for farmers' "resistance" to make permanent water transfers.

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[1] As summarized by Colby (1995, p. 478): "The prior appropriate doctrine, common to western states' water law, gives first priority to the older, most senior water rights with lower priority going to the rights established at a later point in time."

[2] For example, Libecap (2003) notes that in Western states water in urban areas is priced at $200 per acre-foot or more, whereas water prices in agriculture are around $25 per acre-foot. Gollehon (1999) reports that, for the 282 water-market transactions recorded in Western states over 1996-7, permanent transfer prices averaged $1,360 per acre-foot and temporary transfer prices averaged $233 per acre-foot.

Experience over the past twenty-five years of rural market development in Western states confirms that transfers of water rights out of agriculture are generally more controversial than transfers among farmers (Colby 1995; Gollehon 1999; Libecap 2003). Farmers with prior appropriation rights are often unwilling to "trade" water rights permanently, even if they have excess available water to sell.[3] For example, over the 1996-7 period 282 water-market transactions were recorded in Western states, virtually all from agriculture to other uses (72% for urban areas and 10% for environmental purposes) and accounting for 2.7 million acre-feet, or 2.5% of the annual irrigation consumptive use (Gollehon 1999). Permanent transfers accounted for 78% of reported transactions but only 7% of the total water quantity transferred.

The purpose of the following paper is to explore further the economic behavior that underlies this reluctance of farmers to engage in permanent transfer of their water rights. We demonstrate that this behavior may be rational, even in circumstances where farmers do not face periodic drought conditions, uncertainty over available water supplies, or policy and regulatory induced transaction costs. Instead, even in the absence of the latter conditions, farmers may still resist selling their excess water because of the implications for agricultural production growth and welfare. This is an important result, as it suggests that uncertainty of supply and state-imposed transaction costs may not be the only factors influencing farmer behavior towards trading water rights.

We model the relationship between water and growth in the agricultural economy through the perspective of a representative agricultural household that engages in irrigated farming as its principal economic activity. In constructing this model, we follow the general approach to modeling water use and economic growth developed by Barbier (2004), but with some important modifications. Without loss of generality, we assume that three inputs are used in constant returns to scale agricultural production, labor, water and capital broadly defined (to include land and all reproducible capital). Given prior appropriation, water is treated as a private good, but the household faces increasing costs in appropriating and using more water, $r$, from its fixed water right, $w$. We consider two cases. First, where there is a condition of "absolute" water availability constraint, and the household must appropriate its entire water right, i.e. $w = r$.

[3] As explained by Gollehon (1995, p. 58): "There are two broad types of water market transfers. A water sale involves a temporary transfer of water, with the water seller continuing to hold the water right. This type of transfer takes many forms, including single-year rentals, multiyear leases, transfers contingent on water levels, and transfers involving water banks and marketing pools. A permanent transfer of annual water supplies occurs with the ownership change of the water right, whereby an irrigator gives up all future access to the water."

Second, we examine the situation where the household always has excess available water supplies, $r < w$. Under both conditions, we assume that the agricultural household's problem is to choose optimal levels of water use for production and per capita consumption (including household water use) so as to maximize household utility.

Under conditions of excess available water, the agricultural household can attain a long-run saddle point steady state. Along the stable paths leading to this equilibrium, either consumption and capital increase together, or they decline. More importantly, if capital and water are not highly substitutable (the most likely case), water use will rise as the household accumulates capital and increases consumption. This implies that, along the optimal stable path that corresponds to growth in the agricultural economy, water use must also be increasing. However, under conditions of a binding water rights constraint, per capita consumption (and thus welfare) must always be declining. The rate of decline is determined by the household's rate of discount, capital depreciation and the household's elasticity of marginal utility. Along this path, as long as water remains a binding constraint, consumption will decline to zero. But even if excess water is available again, the agricultural household has deviated from the stable path leading to the long-run saddle point equilibrium.

The implication of this analysis is that the agricultural household clearly wants to maintain a situation of excess water supply, as this is the only situation compatible with the optimal path to a long-run equilibrium. In turn, the farming household would be reluctant to sell off "excess water" because of the possibility that this might drive the household into a situation where all available water must be appropriated. This is particularly the case given that the agricultural economy must increase its water use as agricultural production grows. If the agricultural household has perfect foresight, then it would appropriate a sufficient water use right, $w$, initially so that it has excess supplies to accommodate growing water use until the long-run steady state is reached.

The next section describes water use and rights in Wyoming, which is the semi-arid Western agricultural economy that is inspiring our model. Section 3 develops the model of water use by a representative farming household with prior appropriation rights in the agricultural economy. Section 4 analyzes the transitional path and equilibrium conditions for this economy under conditions where the household has "excess water"; i.e., it does not fully use all of its water rights. Section 5 examines the implications of the opposite case where the household must appropriate all its water rights. The final section discusses how these results compare to anecdotal evidence concerning possible explanations why farmers may be reluctant to transfer water rights permanently and the implications for policy.

## 2. Water Resources and Institutions in Wyoming

Wyoming is an ideal "representative" semi-arid Western state with the type of agricultural economy and water issues of interest to this paper.

Wyoming provides the headwaters of four major river basins in western United States. These four river basins are Missouri-Mississippi, Green Colorado, Snake Columbia and Great Salt Lake (Figure 1). Most of Wyoming's surface water endowment flows out of the state by virtue of various inter-state compacts and U.S. Supreme Court decrees governing the allocation of water amongst the Western states. The remaining surface water supplies of 6.4 million acre-feet are used for irrigation, industrial and municipal uses. It is estimated that 1-4 million acre-feet of renewable groundwater is available throughout the state (Jacobs and Brosz, 2000). Thus, Wyoming's unique geography and climate mean that important sectors of the state economy, particularly irrigated agriculture and ranching, are increasingly dependent on available surface and groundwater sources (Wyoming Drought Task Force 2002).

Figure 2 shows the breakdown of annual consumption of surface water and groundwater supplies in Wyoming.[4] Irrigated agriculture is by far the largest consumptive use of surface water in the state (2.3 million acre-feet annually), followed by evaporation from reservoirs (400,000 acre-feet). Irrigation is also the most consumptive use of groundwater (600,000 acre-feet annually). Annual domestic, municipal, industrial and livestock uses are very small in magnitude as compared to irrigation: 60,000 million acre-feet and 100,000 million acre-feet for surface and groundwater respectively. However, a substantial amount of water rights in both

[4] Hydrologists distinguish two concepts of water use: water withdrawal and water consumption (Gleick 2000, p. 41). Withdrawal refers to water removed or extracted from a freshwater source and used for human purposes (i.e. industrial, agricultural or domestic water use). However, some of this water may be returned to the original source, albeit with changes in the quality and quantity of the water. In contrast, consumptive use is water withdrawn from a source and actually consumed or lost to seepage, contamination, or a "sink" where it cannot economically be reused. Thus water consumption is the proportion of water withdrawal that is "irretrievably lost" after human use. For example, in 1995 total global freshwater withdrawals amounted to 3,800 $km^3$, of which 2,100 $km^3$ was consumed.

groundwater and surface water are not used at all in Wyoming, approximately 3.6 million acre-feet of surface water and 1.6 million acre-feet of groundwater.[5]

There are considerable non-consumptive uses, e.g. fishing and recreation, of surface water in Wyoming. These are likely to be increased pressure on available water resources in the state. In 1990, rivers and streams provided about 1.6 million recreational fishing-days per year in Wyoming, and standing waters another 2 million fishing-days. Current demand is estimated at 1.75 million fishing-days per year in rivers and streams, and 2.14 million fishing-days on still water (Jacobs and Brosz 2000). Whereas demand for irrigation water in agriculture is expected to remain unchanged, municipal, domestic and livestock consumption of water is projected to increase from 60,000 acre-feet to nearly 150,000 acre-feet by 2020 – virtually all due to increased domestic and municipal consumption. Industrial consumption of surface and groundwater will increase from 85,000 acre-feet to 845,000 acre-feet, mainly as a result of coal and coal-bed methane developments.

Wyoming water law dates back to territorial days and is based on the "doctrine of prior appropriation." Under this doctrine, the first person to put the water to beneficial use has the first right, meaning "first in time is first in right." Therefore, water rights in Wyoming and in most of the western states are regulated by priority. Those with the earliest rights are entitled to water during periods of limited supply while those with later rights are denied water during such times (Jacobs et. al. 2003).

The state of Wyoming maintains that all water is the property of the state but a person or an entity can obtain a usufructury right (Wolfe 1996). A water right is obtained by applying for a permit to the State Engineer and priority in the queue is determined by the date the application is accepted. Each stream has a list of priorities of water rights. Each water user is responsible not only filing a request for the water right but also for investing in the construction of the structure (e.g. a diversion channel in case of irrigation or a reservoir for stock use) necessary for use of water. Moreover, water has to be put to a demonstrated beneficial use, and the appropriator may have to forfeit the right if water is not used for a period of time (Jacobs et. al. 2003).

In Wyoming, as well as in all Western states, the State Engineer is also responsible for approving the permanent transfer of water rights. As summarized by Brookshire et al. (2002),

[5] Groundwater recharge in Wyoming is estimated to be around 1-4 million acre-feet annually (Jacobs and Brosz 2000). The "unused" water rights from groundwater assume that a total of 2 million acre-feet of annual groundwater recharge available each year.

the prior appropriate doctrine requires three criteria for such transfers to occur: i) the right must be a valid right with a valid priority date, such as pre-1907 or pre-1965; ii) the right must be put to beneficial use; and the right must not impair the rights of others, including compact deliveries.

There are several interesting implications of the prior appropriation mechanism. First, the fact that users have to pay a fixed cost of obtaining the water right (filing of the application to the State Engineer and construction of the diversion structures) as well as the periodic maintenance costs of the diversion schemes means that the monetary costs associated with water use are private to the water right holder. Burness and Quirk (1979) have shown that the queuing of the users leads to unequal sharing of risk, which in turn leads to suboptimal investment decisions by users. That reinforces the idea that once the user receives a water right, the user treats the resulting benefit stream as excludable and non-rival, and therefore maximizes utility from the water right. For these reasons our subsequent discussion of agricultural sector treats water as a private good. There may be important externalities in use (e.g. return flows) but we ignore this complication in our model in order to concentrate on the implications for a farming household of the situation where its water right is fully appropriated as opposed to when it is not.

In sum, given the rising demand for water for municipal, industrial and domestic uses in Wyoming, one would expect there would be a growing market for water rights transfers from farmers. This is particularly the case given that the doctrine of prior appropriation confers water as a private good on the senior user of the water right, the rules for water transfer are fairly transparent and enforceable, and any regulatory and policy-induced transactions costs are not thought to be excessive (Brookshire et al. 2002; Colby 1995; Wolfe 1996). However, out of the 282 water contracts recorded in Western states over 1996-7, only 3 occurred in Wyoming (Gollehon 1999). Only one transfer was a permanent rights transfer, and for 253 acre-feet. Over the 1990-2000 period, only 11 water transactions were recorded for Wyoming, and only two of these were permanent rights transfers (Brookshire *et al.* 2002).

The following model of water use in an agricultural economy illustrates the reasons why farmers in Wyoming and other Western states may be reluctant to make permanent water transfers.

## 3. A Model of Water Use in an Agricultural Economy

The representative consumer in the agricultural economy is a farming household that wants to maximize utility from a per capita bundle of consumption goods $c$.[6] The instantaneous utility function is given by $u(c)$ and we assume that $u' > 0$ and $u'' < 0$.

Irrigated agricultural production on the farm is undertaken by using labor, capital and water. We define "capital" broadly to include not just farm equipment and machinery but also purchased non-labor inputs (e.g. fertilizers, pesticides, seed), farm structures and arable land. We assume constant returns to scale technology, which allows us to represent the production function in the following intensive form, where $y$ is the per capita crop output, $k$ is capital per person and $r$ is per capita water use

$$y = f(k,r), \quad f_k > 0,\ f_r > 0,\ f_{kk} < 0,\ f_{rr} < 0,\ f_{kr} = f_{rk} > 0 \ . \tag{1}$$

The positive cross-partial derivatives imply that capital and water are substitutes.

We assume that the household obtains a fixed quantity of rights to water supply per person, $w$, through prior appropriation, and it therefore treats this available water as a private (exclusive and non-rival) good for its own use for farm production. We model such water appropriation by the household in the following way. In order to utilize an amount of water, $r$, from its total water right for irrigation, the household must allocate a share, $z$, of its aggregate farm output specifically to water supply (e.g. diversion channels, irrigation system etc.) This suggests that $r = zy$. However, assuming that the more accessible water available to the household is utilized first, the household faces increasing costs in appropriating and using more water, $r$, for irrigation from its fixed water right, $w$. That is, the household must allocate an increasing share of its farm output to appropriating water, $z$, as its water utilization, $r$, rises relative to its total water rights, $w$. Denoting $r/w$ as the *rate of water utilization relative to fixed water right held*, it therefore follows that

$$r = z\left(\frac{r}{w}\right)y, \quad z' > 0, z'' > 0,\ \lim_{r/w \to 1} z\left(\frac{r}{w}\right) = \alpha,\ \lim_{r/w \to 1} z'\left(\frac{r}{w}\right) = 0,\ 0 < z, \alpha < 1 \, . \tag{2}$$

The proportion of farm output allocated by the household, $z$, is an increasing function of $r/w$, and the household's water utilization, $r$, rises with output, $y$. Finally, as the household appropriates

[6] For simplicity we assume each farm has one unit of labor and therefore per farm variables are also per capita variables. We also assume that $c$ includes any consumptive (i.e. non-production) water use by the household. However, domestic water consumption is usually negligible for farming households compared to water used for irrigated agricultural production.

all of its available water right, i.e. $\left(\frac{r}{w}\right) \to 1$, the proportion of output appropriated by the consumer to supply water is bounded above by α, but the change in the appropriation rate is zero.[7]

The fixed water right available to the household, *w*, also limits the total amount of water available for irrigation withdrawals. That is, even if the household uses all of its freshwater rights (i.e. $r = w$), water withdrawals are finite. Thus the total per capita water right imposes the following constraint on the household

$$r = z\left(\frac{r}{w}\right) f(k,r) \leq w, \tag{3}$$

with $r = z\left(\frac{r}{w}\right) y < w$ if $0 < \frac{r}{w} < 1$ and $r = z\left(\frac{r}{w}\right) y = w$ if $\frac{r}{w} = 1$.

Denoting T as the rate of capital depreciation, and assuming no population growth (i.e. no increase in the members of the household), capital accumulation is governed by

$$\dot{k} = f(k,r) - \omega k - (c + r) = \left[1 - z\left(\frac{r}{w}\right)\right] f(k,r) - \omega k - c, \quad k(0) = k_0. \tag{4}$$

Any output that is not allocated to appropriating more water, capital depreciation or consumption leads to an increase in the capital stock.[8]

We assume that the representative agricultural household is infinitely lived and discounts future utility at the rate ∗, yielding the following welfare function, *W*

$$W = \int_0^\infty u(c) e^{-\delta t} dt. \tag{5}$$

Maximization of *W* with respect to choice of *c* and *r*, subject to (1) to (4), yields the following Lagrangian expression, *L*, comprising the current-value Hamiltonian for the problem specified by (5) subject to (4), plus the constraint on the control variable *r* given by (3)

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[7] That is, the farming household is allocating a maximum amount of its output, ∀, to extract all of its water right, and thus ∀ is an upper limit on water appropriation by the household.

[8] Derivation of (4) is relatively straightforward. Normalizing the price of the crop output to one, denote *a* as assets per person in the household, *L* as its total population, *w* as the wage rate and *p* as the rate of return on assets. Then the budget constraint and the zero-profit condition of the household are respectively, $\dot{a} = pa + w - (r + c)$ and $L[f(k,r) - (p + \omega)k - w] = 0$. It follows that $\partial y/\partial k = f_k = p + \omega$ and $\partial(Lf(\cdot))/\partial L = f(k,r) - kf_k = w$. Using the latter expressions and assuming that the only assets of the household are its capital stock, $a = k$, then the budget constraint becomes $\dot{a} = \dot{k} = (f_k - \omega)k + (f(k,r) - kf_k) - (r + c)$, which reduces to the left-hand side expression in (4).

$$L = u(c) + \lambda_1\left[\left[1 - z\left(\frac{r}{w}\right)\right]f(k,r) - \omega k - c\right] + \lambda_2\left[w - z\left(\frac{r}{w}\right)f(k,r)\right], \tag{6}$$

where $\lambda_1$ and $\lambda_2$ are the shadow price of capital and water respectively, with the latter representing the scarcity value of irrigation supplies to the agricultural household.

The resulting first-order conditions are

$$u'(c) = \lambda_1 \tag{7}$$

$$\lambda_1\left[(1-z)f_r(k,r) - \frac{z'f(k,r)}{w} + \right] = \lambda_2\left[zf_r(k,r) + \frac{z'f(k,r)}{w}\right], \tag{8}$$

$$\lambda_2 \geq 0,\ w - z\left(\frac{r}{w}\right)f(k,r) \geq 0,\ \lambda_2\left[w - z\left(\frac{r}{w}\right)f(k,r)\right] = 0$$

$$\dot{\lambda}_1 = \lambda_1\left[\delta + \omega - (1-z)f_k\right] + \lambda_2 z f_k \tag{9}$$

$$\lim_{t\to\infty}\{e^{-\delta t}\lambda_1(t)k(t) = 0\}, \tag{10}$$

plus the equation of motion (4).

Equation (7) is the standard condition that the marginal utility of the consumption equals the shadow price of capital $\lambda_1$. Equation (8) determines the optimal allocation of the rate of water utilization of the household, including the complementary slackness condition imposed by the water rights constraint. Equation (9) indicates the change over time in the marginal imputed value of the capital stock of the economy. Finally, equation (10) is the transversality condition for this infinite time horizon problem.

We can derive the optimal path of *c* by differentiating equation (7) with respect to time and using the resulting expression in equation (9)

$$\dot{c} = \frac{u'\left[(1-z)f_k - (\delta + \omega)\right] - \lambda_2 z f_k}{-u''}. \tag{11}$$

The growth of output can be obtained by totally differentiating the production function with respect to time

$$\frac{\dot{y}}{y} = \frac{f_k k}{f}\frac{\dot{k}}{k} + \frac{f_r r}{f}\frac{\dot{r}}{r} \tag{12}$$

Hence output growth rate is weighted average of the growth of capital and water; weights are the share of capital and water in the total product.

Further interpretation of the influence of water use by the household on its welfare and output growth requires examining the conditions under which the water rights constraint (3) is binding or not. We begin with the interior solution in which the household does not appropriate all of its water rights and has excess water available for irrigation.

**4. Case One: Water Rights Constraint Is Not Binding**

If the water rights constraint (3) is not binding, then the complementary slackness condition requires that $w > r$ and $8_2(t) = 0$ for all $t$. For this interior solution, equation (8) reduces to

$$(1-z)f_r = \frac{z'f(k,r)}{w}. \tag{13}$$

When the household has excess water available, it appropriates more water for irrigation, $r$, up to the point where the marginal benefit equals the cost. The marginal benefits $(1-z)f_r(k,r)$, is the net marginal productivity from additional irrigation, whereas the marginal cost, $\frac{z'f(k,r)}{w}$ is the increased output that needs to be allocated to obtain more water for irrigation.

Differentiating (13) with respect to time yields the optimal rate of change in water utilization for irrigation by the household

$$\dot{r} = \frac{\dot{k}\left[\frac{z'}{w}f_k - (1-z)f_{rk}\right]}{\left[(1-z)f_{rr} - 2\frac{z'}{w}f_r - \frac{z''}{w^2}f(r,k)\right]} = \frac{\dot{k}f_{rk}\left[\frac{z'f(r,k)}{wf_k}\sigma - (1-z)\right]}{\left[(1-z)f_{rr} - 2\frac{z'}{w}f_r - \frac{z''}{w^2}f(r,k)\right]}, \quad \sigma = \frac{f_r f_k}{f(r,k)f_{rk}}, \tag{14}$$

where Φ is the elasticity of substitution for the constant returns to scale agricultural production function. The denominator of (14) is negative. The numerator of (14) is also negative when Φ is very small, implying a low level of substitution between capital and water in crop production. This is likely to be the case for irrigated agriculture, and thus (14) suggests that capital accumulation by the household is likely to result in growth in water use for irrigation.

The remaining dynamic equations for the agricultural economy's optimal path when the household does not face a binding water rights constraint are condition (4) for capital accumulation and

$$\dot{c} = \frac{u'\left[(1-z)f_k - (\delta + \omega)\right]}{-u''} . \tag{15}$$

Consumption in the agricultural economy, and thus welfare, will increase over time if the marginal productivity of capital, net of water appropriation, exceeds the household's discount rate plus the rate of capital depreciation.

Returning to (12), it follows that agricultural output will increase as the household invests in more capital and increases water use for irrigation. Hence in an agricultural economy where water rights are not a binding constraint on appropriating more water for irrigation, growth in capital is likely to be accompanied by a growth in water use and thus agricultural output growth.

Equation (14) indicates that, when excess water is available to an agricultural household, the rate of water use is determined solely the rate of capital accumulation. We can therefore characterize the long-run equilibrium $\dot{c} = \dot{k} = \dot{r} = 0$ for the household by the two-equation system

$$c^* = \left[1 - z\left(\frac{r^*}{w}\right)\right] f(k^*, r^*) - \omega k^*, \qquad \dot{k} = \dot{r} = 0 \tag{16}$$

$$\left[1 - z\left(\frac{r^*}{w}\right)\right] f_k(k^*, r^*) = \delta + \omega, \quad \dot{c} = 0 \tag{17}$$

Condition (16) states that the steady-state level of consumption per capita of the household is determined by farm output that is not allocated for water utilization or capital depreciation. Condition (17) indicates that, in the long run, the marginal productivity of capital, net of water appropriation, must equal the household's discount rate plus the rate of capital depreciation.

The transitional dynamics of the agricultural economy and the long-run steady state, which is a local saddle point equilibrium, are depicted in $(c,k)$ space in Figure 3.[9] If the agricultural household begins with an initial amount of capital below the long-run equilibrium level, $k_0 < k^*$, then as depicted in the figure, the optimal saddle path to the steady state, *AB*, is

[9] As noted, (14) is determined recursively by (4). Thus, the true dynamic path of the system is represented by equations (4), (13) and (15). Totally differentiating this system and using the result from (13) to derive *dk/dr* for substitution in (15), one gets for (4) $d\dot{k}/dc = -1 < 0$ and for (15) $d\dot{c}/dk < 0$, which when evaluated at the steady state $(k^*, c^*, r^*)$ are necessary conditions for that equilibrium to be a saddle point. The proof is available from the authors on request.

positively sloped. Along this path, capital is accumulating and thus water use in increasing, i.e. $\dot{r} > 0$. From (12) and (15), it follows that crop production, consumption and thus welfare is also increasing. In the long run, the agricultural economy settles down the steady state ($k^*, c^*, r^*$), but the household never appropriates all of its water rights, i.e. $r^* < w$.

### 5. Case Two: The Water Rights-Constrained Economy

In this case, from the outset the agricultural household must always appropriate all of its water rights, i.e. $r = w$. From the complementary slackness condition for (8), $\lambda_2(t) > 0$ for all $t$. Also, from (2) $\lim_{r/w \to 1} z\left(\frac{r}{w}\right) = \alpha$ and $\lim_{r/w \to 1} z'\left(\frac{r}{w}\right) = 0$. That is, the proportion of farm output appropriated by the household for providing irrigation water is equal to the constant maximum rate, α.

First-order condition (8) now becomes

$$\lambda_1(1-\alpha)f_r - \lambda_2 \alpha f_r = 0 \quad \textbf{or} \quad \lambda_2 = \frac{1-\alpha}{\alpha}\lambda_1 = \frac{1-\alpha}{\alpha}u'. \tag{18}$$

The scarcity value of irrigation supplies to the household must equal the latter's marginal utility of consumption weighted by the relative share of farm output that is not used to appropriate water.

Similarly, the dynamic equations for capital and consumption per capita are, respectively

$$\dot{k} = (1-\alpha)f(k,r) - \omega k - c \tag{19}$$

$$\dot{c} = \frac{u'[(1-\alpha)f_k - (\delta+\omega)] - (1-\alpha)u'f_k}{-u''} = \frac{(\delta+\omega)u'}{u''} < 0 \tag{20}$$

For the water rights-constrained economy, per capita consumption is always declining. Dividing both sides of (20) by $c$, one can see that the proportionate rate of decline is equal to the rate of capital depreciation plus the discount rate, δ + ω, divided by the elasticity of the marginal utility of consumption, $\nu(c) = u''c/u' < 0$. If per capita consumption is falling, then the marginal utility of consumption is rising over time. The more responsive is this latter effect, the less consumption is falling along the optimal path of the agricultural economy. Finally, although consumption per capita is always declining, equation (19) suggests that capital accumulation could be increasing, constant or falling along the optimal path.

Figure 3 depicts one possible path, *AC*, for the water-rights constrained agricultural economy starting at initial capital level $k_0$, and with capital accumulation occurring throughout, but with $r = w$ and consumption per capita always falling. Note that the slopes of the four isosectors depicted in the figure no longer hold, and the path *AC* will diverge from the long-run saddle point steady state ($k^*, c^*, r^*$). In fact, because consumption (and thus welfare) is always declining for the agricultural household, the latter steady state is unattainable for any optimal path for the water-rights constrained agricultural economy.

Returning to equation (12), with a constant irrigation input $r = w$ but with capital accumulation occurring, agricultural output will grow in the short run. However, in the long run, diminishing returns to capital will ensure that continued growth in the capital stock will result only in output stagnation.[10] Thus, as indicated in Figure 3, path *AC* for the water-rights constrained agricultural economy is likely to lead to an outcome in the long run where per capita household consumption is zero, and both capital stock and crop output are constant values, $(\bar{k}, \bar{y})$, with the latter just offsetting capital depreciation and water appropriation, i.e.

$\bar{y} = f(\bar{k}, r) = \omega\bar{k} + \alpha\bar{y},\ \dot{\bar{k}} = 0,\ r = w$.

## 6. Discussion and Conclusions

We have shown that, provided the agricultural household does not fully use its water rights, it can attain an optimal growth path in capital accumulation and consumption to a long-run saddle point equilibrium. Along this optimal stable path that corresponds to growth in the agricultural economy, water use must also be increasing. However, provided that there is always excess water available for irrigation, i.e. $r < w$, then there is no constraint on either agricultural growth or increasing welfare for the household.

In contrast, under conditions of a binding water rights constraint, per capita consumption (and thus welfare) must always be declining. Along this path, as long as water remains a binding constraint, consumption will decline to zero. But even if excess water is available again, the agricultural household has deviated from the stable path leading to the long-run saddle point equilibrium.

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[10] This is the result of the Inada conditions for a neoclassical production function such as (1), i.e. $\lim_{k\to\infty} f_k = 0$. From (12), with constant irrigation $r = w$, it follows that $\lim_{k\to\infty} \frac{\dot{y}}{y} = 0$.

The implication of this analysis is that the agricultural household clearly wants to maintain a situation of excess water supply, as this is the only situation compatible with the optimal path to a long-run equilibrium. In turn, the farming household would be reluctant to sell off "excess water" because of the possibility that this might drive the household into a situation where all available water must be appropriated. This is particularly the case given that the agricultural economy must increase its water use as agricultural production grows. If the agricultural household has perfect foresight, then it would appropriate a sufficient water use right, $w$, initially so that it has excess supplies to accommodate growing water use until the long-run steady state is reached. Alternatively, if the household did want to sell its water rights permanently, it is likely to do so only if it plans to get out of agriculture entirely. The risks to the household of staying in agriculture and being forced into a water-rights constraint where irrigation is limited to $r = w$ are too great, so if the household is going to transfer its water rights permanently, then it might as well sell the entire rights and leave the agricultural economy.

We believe that the results of this analysis are a plausible explanation of the reluctance of farmers to engage in water markets and make permanent water rights transfers, even without assuming the presence of policy or regulatory-induced transaction costs, uncertainty due to drought and water shortages and externalities. Of course, the latter factors are also important, but they work to further reinforce the reluctance of farmers to engage in water rights transfers. For example, if uncertainty over drought and future water shortages means that a farmer is less sure of how much of his or her existing water right, $w$, would actually be available for future irrigation, $r$, then the farmer would be even less willing to sell permanently some of that water right, even if the farmer appears to have excess water available for irrigation today.

Some anecdotal evidence from water rights transactions in Western states supports the results of our analysis. For example, Gollehon (1999, p. 61) notes that, in most permanent water transfers from agricultural to other uses, "the compensated sellers often cease irrigation", which implies that such permanent sales occur when farmers and rural communities consider leaving the agricultural economy altogether.[11] Similarly, a case study of groundwater transfers from

[11] Gollehon (1999, p. 61) also observes that "many rural communities have been in economic decline for some time, and attributing the reduced economic activity to the water transfer may be difficult." In fact, our model shows that in the latter scenario selling the entire water rights, $w$, may be a rational strategy for an agricultural economy facing permanent decline. For example, suppose in Figure 3 the agricultural household begins with a capital stock lower than long-run steady state levels, i.e. $k_0 > k^*$. Although not shown, the optimal stable path for the economy would be to choose initially a high level of consumption but one with perpetually falling consumption, capital and water use until the steady state is reached. Rather than be faced with this scenario, the household is likely to be willing to

agricultural to urban uses in La Paz County, Arizona in the 1980s indicated that 40,000 irrigated acres out of a total of 48,000 acres would be idled by the permanent water rights transfers, and the remaining 8,000 acres would continue to operate only until the additional surface water available to the farmers for irrigation would be needed by the urban areas (Charney and Woodward 1990). A case study of agricultural to urban water transfers in the Arkansas River Valley, Colorado also estimated that the approved and pending transfers account for over 60 percent of the study area's water, with an associated idling of almost 60% of the irrigated land (Howe et al. 1990). Due to backward and forward linkages to suppliers and processors for a significant portion of the irrigated agriculture, regional employment and income effects across the entire rural economy were also estimated to be severe.

Equally important in explaining the reluctance of farmers to engage in permanent water transfers is the general perception in rural areas that such transactions may not be beneficial. For example, in commenting on a survey of rural communities in La Paz County, Arizona "in attempt to better understand concerns about various nonpecuniary threats to rural areas of origin" from the proposed transfers, Charney and Woodward (1990, p. 1198) note that: "One principal finding was that 93% of the respondents in La Paz County agreed with the statement, 'The losses to the community associated with the transfer of water are of such a nature that they cannot be compensated." In addition, the respondents stated that their overall perception was that "private well owners, indigenous groups, future generations, and small farms tend to lose."

Finally, even if farmers do not intend to sell their entire water rights, they are reluctant to do so as they value the additional safety net of having additional water supplies available. For example, Libecap (2003, p. 11) considers an important additional "transaction" cost preventing permanent water transfers between agricultural and non-agricultural uses in semi-arid Western states; i.e., "transfers of some agricultural water to urban areas could place that agriculture at risk if a serious drought occurs. This condition makes it difficult for farmers to release part of their water rights since they lose the cushion that could protect them during drought." As our model shows, there are serious consequences to the agricultural economy, if farmers are constrained by an "insufficient" water right to meet irrigation needs.

sell its water rights $w$ at the outset to a non-agricultural user paying premium prices and leave the agricultural economy.

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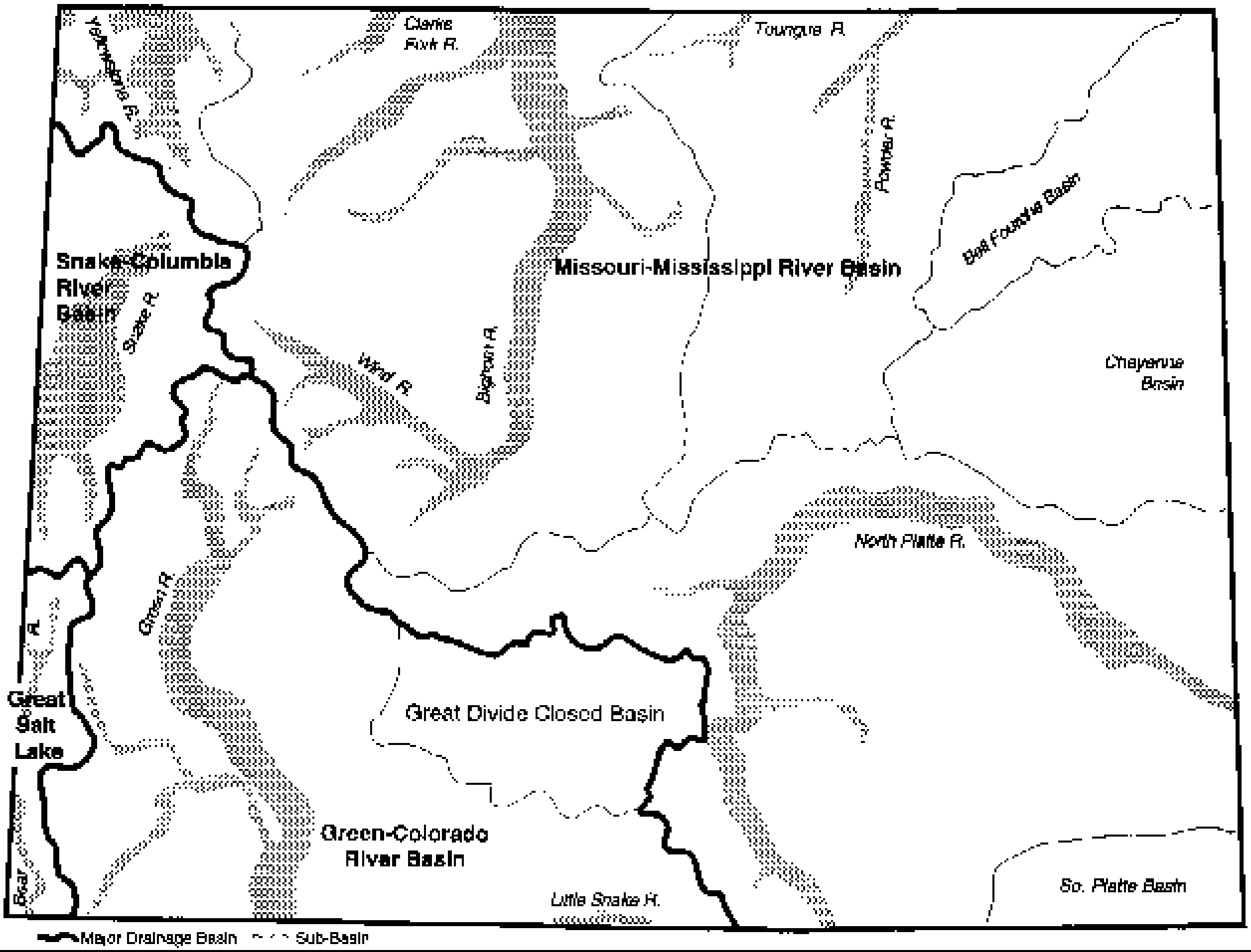
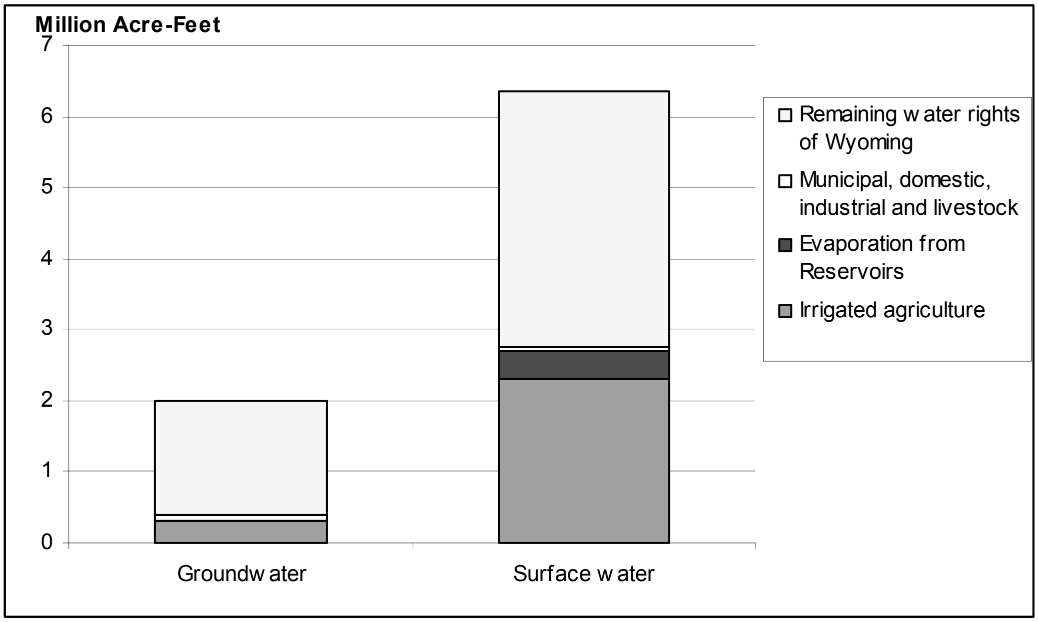
**Figure 1. Major Rivers of Wyoming**




Source: US Geological Service

**Figure 2. Annual Consumption of Groundwater and Surface Water in Wyoming**




Source: Jacobs and Brosz (2000).

**Figure 3. Optimal Paths for the Agricultural Economy**