WHY IMPROVING IRRIGATION EFFICIENCY INCREASES TOTAL VOLUME OF CONSUMPTIVE USE

POURQUOI L'AMELIORATION DE L'EFFICACITE DE L'IRRIGATION AUGMENTE LE VOLUME TOTAL DE L'USAGE A LA CONSOMMATION

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ABSTRACT

The common prescription for dealing with limited supplies of water is to improve irrigation efficiency, that is, to reduce gross delivery to farm fields while maintaining full crop production. The public and some policy makers continue to assume that the water thus saved constitutes a new supply that may be applied to other uses. Scientists and hydrologists have long understood that the non-consumed fraction of applied water often becomes the source for another human or ecosystem purpose after leaving the field, and irrigation improvements interrupt these uses. Thoughtful researchers have provided valuable guidance in conceptual frameworks and analysis procedures to address this issue.

Researchers have also noted empirically that total consumptive use often increases when efficiency improves, and have cited case-specific reasons that this occurs. This paper shows it is a general case arising from rational producer behavior in equating the marginal cost of a production input (irrigation water) with its marginal benefit. At any marginal cost of water, improving irrigation efficiency enables the irrigator to be willing and able to purchase a quantity of irrigation water that sustains more consumptive use than was possible with the prior, less-efficient system.

An equation for economic demand for water is presented where impacts to both crop yield and commodity price are endogenously determined from simple input data. It is applied to an irrigated area in Idaho, USA where it indicates that improving efficiency from 60 percent to 80 percent reduces field delivery of irrigation water by 15 percent but increases consumptive use by three percent.

RÉSUMÉ ET CONCLUSIONS

La prescription universelle visant à étendre l'approvisionnement limité en eau consiste à améliorer l'efficacité de l'irrigation, qui est habituellement définie comme la réduction de l'alimentation brute en eau tout en maintenant l'intégralité de la production des récoltes. Le public pense que l'application excessive de l'eau est gaspillée et que sa récupération devrait fournir de l'eau supplémentaire pour d'autres usages et d'autres projets.

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L'eau approvisionnée qui n'est pas utilisée pour la consommation devient généralement une fourniture destinée à d'autres utilisateurs ou écosystèmes. Interrompre ce flux en améliorant l'efficacité a des ramifications au sein du budget prévu pour l'eau et les hydrologistes l'ont reconnu depuis longtemps. Les scientifiques et exploitants les plus progressistes évaluent soigneusement les impacts de l'accès à l'eau « économisée », mais également les effets de la réduction du flux vers ceux qui précédemment comptaient sur l'eau « gaspillée ».

Outre ces questions relatives au budget en eau et à la redistribution, améliorer la gestion ou l'infrastructure afin de réduire la part non consommée de l'eau d'irrigation mise en application a révélée, empiriquement, l'augmentation paradoxale de la consommation totale. Des explications relatives à un cas spécifique de ce phénomène sont généralement disponibles. Toutefois, ce résultat observé est un résultat général d'économie en matière d'eau d'irrigation telle une donnée d'un processus de production. C'est ce à quoi il faut s'attendre dès lors que la part non consommée de l'eau appliquée est réduite.

L'approche type pour estimer la demande économique d'un facteur de production est de quantifier la valeur marginale que les intrants ajoutent au processus de production. Le prix que les producteurs veulent bien payer sera équivalent au revenu marginal fourni par l'augmentation des intrants supplémentaires. Dans le cas du facteur de production « eau d'irrigation, » la valeur marginale de production provient des répercussions à la fois sur la quantité et la qualité des récoltes comme cela est reflété par les prix des récoltes. Les répercussions en matière de quantité peuvent être étudiées plus en avant en cloisonnant le devenir de l'eau appliquée en transpiration au travers des végétaux, l'évaporation directe du sol et des surfaces des végétaux, l'écoulement et la percolation. Combiner ces effets et trouver un dérivé du revenu concernant le volume d'application permettent une représentation mathématique explicite de la demande économique pour l'eau d'irrigation.

Les parts d'eau qui se transforment en évaporation, en écoulement et percolation changent à divers niveaux d'irrigation et sont commandées par l'infrastructure et la gestion de l'irrigation. Ceci façonne la fonction de production et peut être utilisé pour calculer le volume d'usage à la consommation lié au volume appliqué. Les relations précisent que l'adoption d'un régime d'infrastructure ou d'une gestion qui réduit la fraction de l'eau non consommée (à savoir, gaspillée) augmente toujours le volume total consommé (évaporation plus transpiration). Conceptuellement, un irrigateur doit payer pour l'intégralité du volume appliqué, mais retire le bénéfice économique uniquement du volume consommé. Tandis que les améliorations en gestion lui permettent de payer pour une moindre quantité ou une quantité d'eau non productive, il faut donner plus d'argent pour payer l'eau consommée supplémentaire.

Un exemple de calcul de la *Eastern Snake River Plain* dans l'Idaho, É. U.A. indique qu'une augmentation de la fraction utilisée pour la consommation de l'eau appliquée de 60 à 80 pourcent réduirait le volume de diversion de 1,3 million de mètres cubes par an mais augmenterait l'usage à la consommation de 200 000 mètres cubes. L'effet net sur l'alimentation en eau repose sur le fait de savoir si l'augmentation de l'usage à la consommation serait compensé par une diminution du flux d'écoulement ou de percolation vers des puits non utilisables tels que des aquifères extrêmement profonds ou saumâtres ou des lacs alcalins ou des mers.

1. INTRODUCTION

BACKGROUND

On a planet with increasing demand for a finite supply, fresh water is the "The New Oil" or "Blue Gold". Following the hyperbole, the foremost solution to the "World Water Crisis" is water conservation from agriculture. Irrigated agriculture is targeted for conservation because irrigated agriculture accounts for about 70% of the global water withdrawals (Johnson et al 2001), world-wide on-farm irrigation efficiency ranges from 25 to 50% (Brown, 2006), and agriculture is the least valued water user. It is asserted that in California (USA) alone, "improvements [in irrigation] could potentially conserve roughly five million acre-feet [6×10^9 m^3] of water per year..." (Kingsolver, 2010). When public funds are expended to conserve water, it is typical to earmark expected water savings for some explicitly identified purpose (Scheierling et al, 2004).

Expenditures, plans and expectations for such projects must be compatible with the physical reality of what will happen with their adoption. This paper examines what actually occurs when improvements in management and/or technology reduce the fraction of field-applied water that does not support crop evapotranspiration, generally termed an improvement in irrigation efficiency. The paper attempts to rely upon fractions terminology rather than the now-ambiguous term "efficiency" (Willardson et al, 1994; Perry et al, 2009).

EMPIRICAL OBSERVATIONS

A conceptual and practical problem with water-savings programs arises when the water savings is accomplished by interrupting a stream of non-consumed water exiting the irrigated lands, which is already relied upon for other economic activity or for ecosystem services. In that case the saved water is not a new supply, but is a reallocation from an existing use. Many investigators have recognized this difficulty and explained it eloquently, including Willardson et al (1994), Huffaker and Whittlesey (2003), Perry (2007), Huffaker (2008) and Hanak et al (2010). The State of Colorado, USA prevents reallocation of allegedly saved water, under the presumption that the interrupted unused excess stream is likely to have been a source for some other use (Morea et al, 2011).

In addition, empirical observations have often noted that improvements in technology or management can increase consumptive use, reducing basin water supply. A wide-scale field study found that crop evapotranspiration on "drip/micro is 6 - 10% higher... than under surface or sprinkler irrigation" (Burt et al, 2002). Scheierling et al (2004) state that "consumptive use may not decrease - it may even increase." Perry et al (2009) caution that "savings... are not guaranteed and must be critically evaluated" while Huffaker and Whittlesey (2003) simply assert that consumptive use "will increase."

Three mechanisms are offered when improved irrigation technology or management increases consumptive use:
>1) Site-specific physical characteristics of the irrigation system are invoked. For example, Burt et al (2002) explain that drip irrigation wets only part of the soil surface, but for longer periods of time.
>2) Water saved will be applied to new uses or expanded acreage within the irrigated region (Huffaker and Whittlesey, 2003; Scheierling et al, 2004; Ward and Pulido-Velazquez, 2008).
>3) Improved technology and management produce higher crop yields, increasing consumptive use even without increased acreage. (Willardson et al, 1994; Perry, 2007; Scheierling et al, 2004).

GENERAL CASE

While these mechanisms are important and correct, the economics of production inputs are sufficient to demonstrate a general case. Changing technology and/or management to reduce the non-consumptive (loss) fraction under full-supply conditions will increase absolute consumptive use except under very low marginal costs for water. Rational irrigators will apply the quantity of a production input (irrigation water) that equates the marginal cost of the input with the marginal revenue it adds to production. Conceptually, only consumed water is an input into the crop-production process. From the irrigator's viewpoint, the non-consumed water that must also be obtained and delivered is non-productive. Technology and management that reduce this non-productive fraction give a greater ratio of productive consumed water to total applied water, and therefore the per-unit cost of the productive fraction is reduced. At any non-zero marginal cost of field-delivered water, a user with less losses is willing and able to purchase enough water to sustain production levels that consume more water than can his/her counterparts, who also pay for the full delivered volume but lose a greater fraction of water.

A mathematical demand function that illustrates the general case is outlined. Following the demand function, a case study evaluates diversion volume and consumptive-use volume in the Eastern Snake River Plain of Idaho, USA under two different assumptions of consumptive-use fraction of field-applied water at full irrigation.

2. PHYSICAL RELATIONSHIPS AND MATHEMATICAL DESCRIPTION

Evapotranspiration and yield

An approximately linear relationship exists between yield and crop evapotranspiration (ET), as shown in Equation (1) (Doorenbos et al, 1979; Allen et al, 1998). The linear relationship is strongest for crops where the harvested portion is a large fraction of dry matter (Doorenbos et al, 1979). Equation (2) modifies the relationship for a threshold of dry-matter production that contributes to ET but does not produce yield (Grismer, 2001). In Figure 1, the Doorenbos relationship is line (Ya) and the Grismer relationship is line (Yb). This paper relies upon the Doorenbos relationship.

$$Y = K1 \, (ET) \qquad\qquad (1)$$

$$Y = K1(ET) + K2 \qquad\qquad (2)$$

Where Y $\quad$ = total dry-matter production (tonne/ha);
$\quad\quad$ K1 $\quad$ = slope coefficient (tonne/ha/m);
$\quad\quad$ ET $\quad$ = crop evapotranspiration (m); and
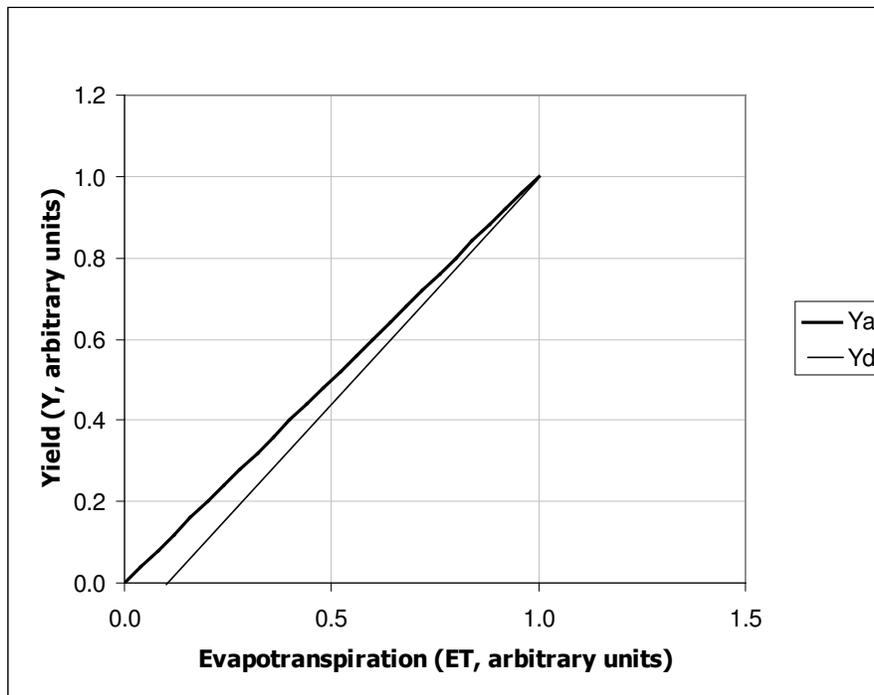$\quad\quad$ K2 $\quad$ = negative intercept coefficient (tonne/ha)

Figure 1. Theoretical relationships between evapotranspiration and yield from Doorenbos (Ya) and Grismer (Yd). (Relations théoriques entre l'évapotranspiration et le rendement Doorenbos (Ya) et Grismer (Yd)).

While the governing physical relationship is actually between transpiration and yield (Allen et al, 1998; Perry, 2009), a simplifying assumption is made that evaporation will be approximately proportional to transpiration. Since both evaporation and transpiration are lost from the hydrologic basin, evapotranspiration is the quantity of interest here.

Applied Irrigation water and yield

In contrast to the linear relation of evapotranspiration to yield, the marginal productivity of applied water is a curvilinear function. No irrigation system is able to deliver 100% of the field-applied water to consumptive use. As the depth of irrigation increases, a decreasing proportion of applied water contributes to production. This physical relationship gives rise to a typical production function of diminishing marginal productivity. Beyond a certain depth, it is empirically observed that marginal productivity becomes negative and yields are reduced. Physically this is explained by reductions in soil aeration, increased plant diseases and nutrient leaching (e.g. Zand-Parsa et al, 2001).[3] In Figure 2, the linear Doorenbos ET/yield relationship (Ya), is contrasted with the applied-water production function (Yb) and its region of negative marginal productivity (Yc).

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[3] The production functions of Zand-Parsa et al (2001), English (1990) and English and Raja (1996) are compatible with those used here, though this paper assumes applied volume is an irrigator decision influenced by marginal cost and marginal revenue constrained by availability, rather than a fixed endowment.
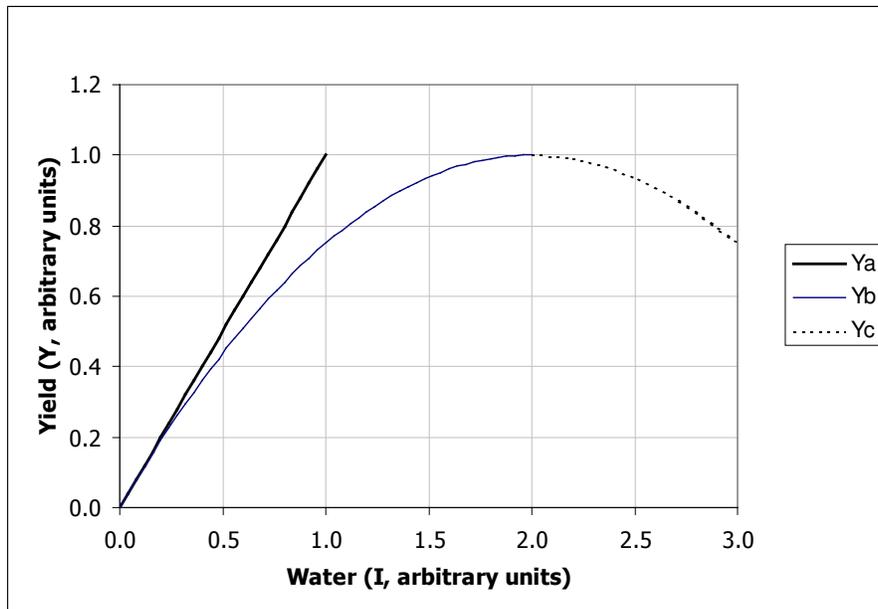
Figure 2. Theoretical water production functions (Fonctions de production d'eau théoriques).

The specific functional form developed by Martin et al (1984) will be used in this study. This form describes the rational production region; the part of the applied-water production function where marginal returns are positive but declining. Doorenbos' ET/yield relationship is implicit in this equation.

$$Y = Ym - (Ym - Yd)(1 - I/Im)^a \qquad (3)$$

Where Ym = yield at full irrigation (tonne/ha);
Yd = rain fed yield (tonne/ha);
I = irrigation depth (m);
Im = irrigation depth for full yield (m);
a = $1/B$ (unitless);
B = consumptive-use fraction of applied irrigation water at full yield (unitless), calculated as $(ETm - ETd) / Im$;
ETm = evapotranspiration at full yield (m);
ETd = evapotranspiration under rain fed conditions (m).

Demand for applied irrigation water

Economic demand for a production input is a derived demand. Producers value inputs only from the benefit they add to the production process; demand for the input is derived from the production it enables. Typically, as more and more of an input is employed, each additional increment adds less to production than the one before. Rational producers will maximize the difference between the Total Cost (TC) of the input and the total revenue it produces (Total Revenue Product or TRP). This point occurs where the first derivatives (slopes) of the cost and production functions are equal. This may be termed the point where Marginal Cost (MC) equals Marginal Revenue Product (MRP). In lay terms, this is the point where one additional monetary unit of input produces exactly one monetary unit worth of increased product.

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Irrigation water is an input to crop production and its demand is a derived demand. Irrigators maximize returns by equating marginal revenue from irrigation with marginal cost of applied water. Revenue from irrigation depends both on the production function and the crop price. For irrigated crops, revenue is defined as crop yield [Equation (3)] times commodity price, and marginal revenue is the first derivative of revenue with respect to irrigation depth. Assuming an exogenous commodity price (see English, 1990; Zand-Parsa et al, 2001) Contor et al (2008) derived the demand for depth of irrigation water on a unit area, as a function of marginal water price:

$$I = Im - Im \left[(Im\ B\ Pw) / (P\ (Ym - Yd)) \right]^{(1/(a-1))} \qquad (4)$$

Where Pw   = price of water depth (currency/m);
       P   = price of crop (currency/tonne).

Equation (4) ignores the fact that crop quality and therefore commodity price are also dependent upon irrigation adequacy. For example, as potato yields decline due to water stress, quality also declines and farmers are subject to price penalties. An exponential relationship is used as a placeholder for the price/yield relationship, pending future investigation into the proper functional form:

$$P = Pm\ (Y / Ym)^Z \qquad (5)$$

Where Pm   = commodity price for a fully-irrigated crop (currency/tonne)
       Z   = empirical parameter (unitless).

Thus, differences between Y and Ym resulting from moisture deficiency would be accompanied by a reduction in crop quality and commodity price. A value of Z equal to zero is the case where crop prices are exogenous or constant at all levels of production, as assumed in Equation (4). Figure 3 illustrates relationships between price and yield at three levels of parameter Z. Lower values of Z are perhaps typical of forage crops, while higher values are conceptually typical of some fruits and vegetables.

The product of Equation (3) times Equation (5) gives revenue per depth (on a unit area) with both yield and commodity price endogenously determined by irrigation adequacy and effective precipitation. Taking the first derivative with respect to irrigation depth gives the economic demand for irrigation depth:

$$\partial R/\partial I = Pm\ [(Ym - (Ym - Yd)\ (1 - I/Im)^a)/Ym]^Z * [(a/Im)\ (Ym - Yd)\ (1 - I/Im)^{(a-1)}]$$
$$* [Ym - (Ym - Yd)\ (1 - (I/Im))^a] * [Z\ Pm\ [1 - (1 - Yd/Ym)\ (1 - I/Im)^a]^Z *$$
$$[(a/Im)\ (1 - Yd/Ym)\ (1 - I/Im)(a-1)]] \qquad (6)$$

Input variables for Equation (4) and Equation (6) are not independent, but have been selected for convenience of obtaining data. For instance, Im and B are functionally related; one must not be modified without adjusting the other. Similarly, the relationship between Yd and Ym is not independent of the relationship between ETd and ETm.

When exponent Z is large the marginal revenue function does not exhibit decreasing marginal returns to irrigation across all depths; at low depths of irrigation, the combined effect of increasing yields and increasing prices is that marginal returns are increasing with additional application.
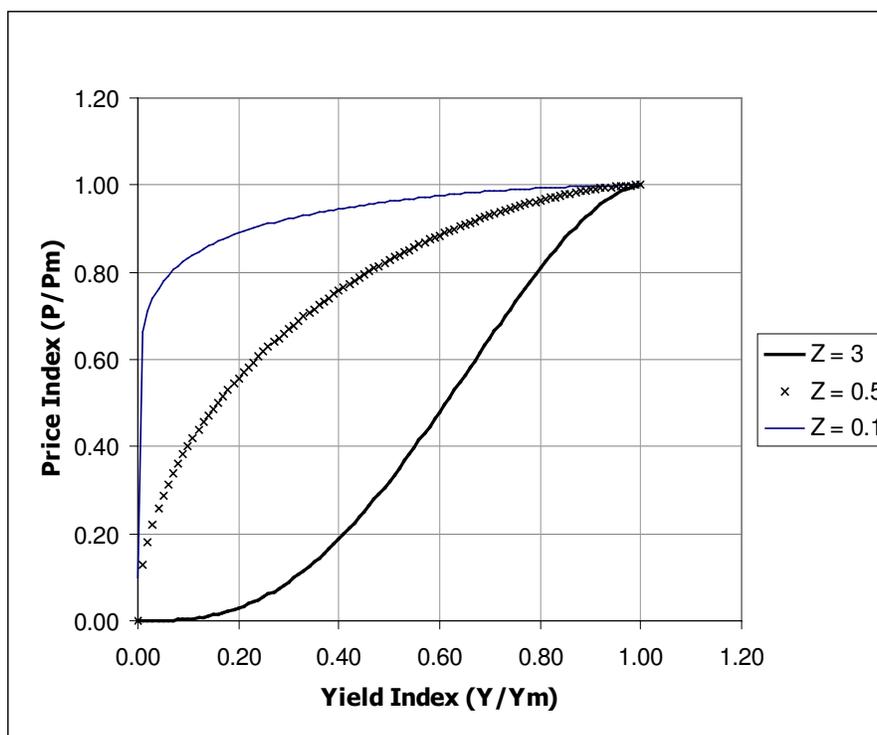
Figure 3. Relationship of commodity price to crop yield for three values of parameter Z (Relation du prix de commodité pour le rendement des récoltes pour trois valeurs de paramètres Z).

In Figure 4 the transition from increasing to decreasing marginal returns occurs at approximately 60% of full irrigation depth, the point of highest marginal revenue.[4] Rational irrigators will not apply less than this depth. Rather than continue to reduce application depth, they will concentrate available water on the number of hectares that can be served with the depth of maximum $\partial R/\partial I$. As water supply increases and all available lands become irrigated, additional water must cause depth to increase and the region of decreasing marginal returns is encountered. From this point, the demand function becomes downward sloping as typically expected for a normal good. This is illustrated in Figure 5, where $\partial R/\partial I$ is the marginal revenue per depth of water on a unit area and R' is the willingness-to-pay. Figure 5 assumes the ability to maintain the depth of maximum $\partial R/\partial I$ (in this case, approximately 0.9 meter) when water is scarce, by concentrating application to only part of the unit parcel and leaving the rest of the parcel not irrigated.

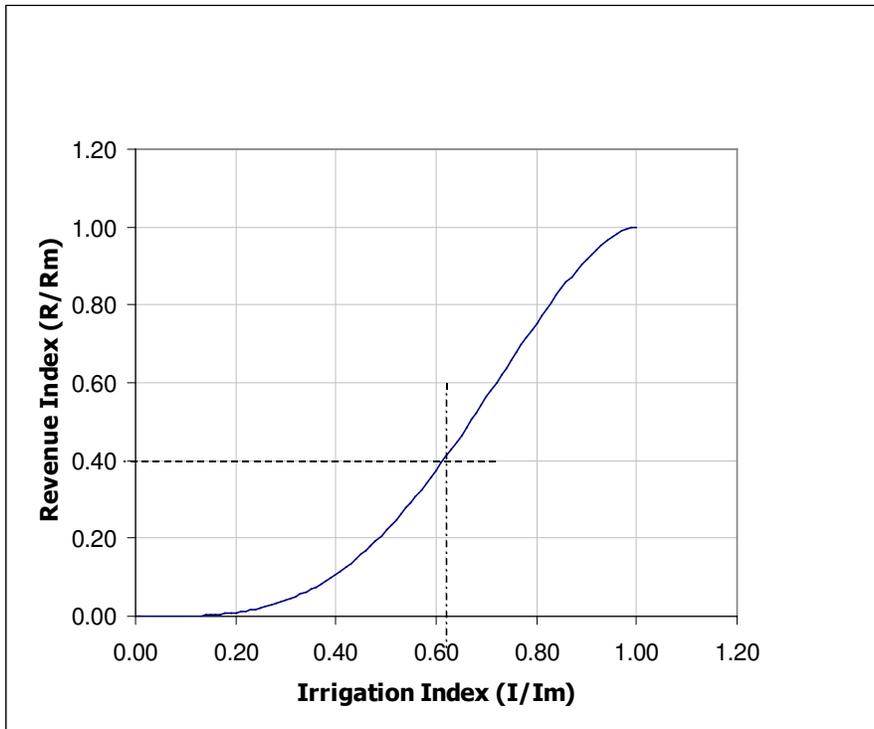[4] The exact shape of this curve and the location of the transition depend on (ETd/ETm), B and Z.

Figure 4. Transition of revenue curve (R/Rm) from increasing marginal returns to decreasing marginal returns (Transition de la courbe de revenu (R/Rm) de l'augmentation du rendement marginal à la diminution des rendements marginaux).
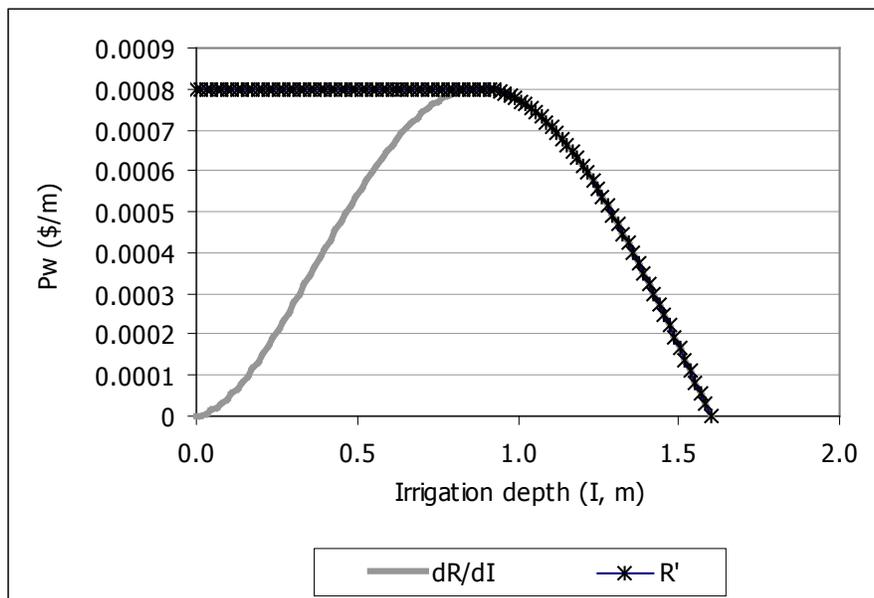

Figure 5. Marginal revenue (∂R/∂I) and willingness to pay (R') for depth of irrigation water (Revenu marginal (∂R/∂I) et volonté de payer (R') pour une profondeur de l'eau d'irrigation).

Equation (4) directly gives depth of irrigation (I) as a function of price of water (Pw). Equation (6) is not easily inverted, but the willingness to purchase as a function

of marginal cost may be found graphically or by numerical approximation. Once the irrigation depth is estimated, yield (Y) may be found using Equation (3). Finally, total ET is found using Equation (1) and then ET from precipitation is subtracted to give ET from irrigation. Figure 6 shows the results for three levels of consumptive use fraction of applied irrigation (B), with parameter (Z) equal to 2.0. The increase in willingness to purchase with increasing B is general for other levels of parameter Z.
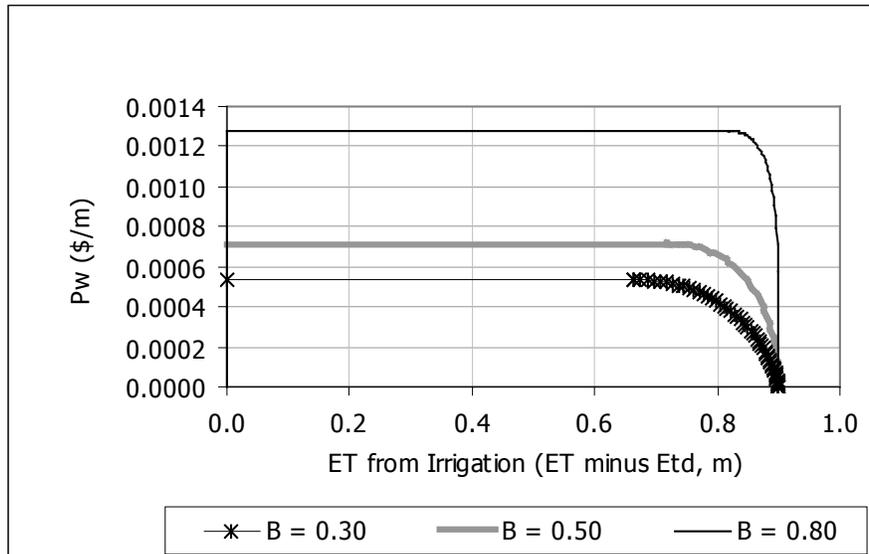

Figure 6. Relationship of evapotranspiration to water price for three values of parameter B (Relation du l'évapotranspiration pour prix de l'eau pour trois valeurs de paramètres B).

Estimation of aggregate demand

The demand for irrigation water [Equation (6)] is for a single crop on a unit land area. To obtain a demand for a volume of water on a given parcel, the irrigation depth is multiplied by area. Parcels are aggregated to give regional results. Aggregate demand is the horizontal summation across parcels; that is, at each price in the demand schedule, the quantities demanded for all parcels are summed. The demand estimated is short-run demand at the field delivery point.

In multiplying the results of Equation (6) by crop area and summing across crops, the status-quo crop portfolio is implicit. It is assumed that the observed crop mix reflects all the agronomic, economic, management and physical constraints that force lower-revenue crops to be grown, rather than every hectare being planted to high-revenue crops. The operation of horizontal summation allows these constraints to be reflected across the range of water prices considered. At first glance, a criticism of this assumption is that it seems counter to the empirical observation that crop mix shifts towards a greater proportion of high-revenue crops as water becomes more costly. However, horizontal summation of demand actually accommodates this observation. Suppose a farm where three crops are planted at the current water price, 33% of the land to the high-revenue crop and 33% to the low revenue crop. As water prices increase, application depths will decrease. The aggregate demand shows the price at which the farmer becomes unwilling to apply water to the low-revenue crop. At the point where 33% of the land is non-irrigated, none of the low-revenue crop will be irrigated and the other two crops will comprise the irrigated crop mix. As marginal water costs increase to the point that 67% of the land is non-

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irrigated, all the remaining irrigated hectares will be planted to the high-revenue crop.[5] The alternative to this assumption is to explicitly identify, parameterize and model all of the binding constraints (Gutiérez-Castorena et al, 2008; Cortignani and Severini, 2009).

3. APPLICATION TO THE EASTERN SNAKE RIVER PLAIN OF IDAHO

To demonstrate and test the practical effects of these relationships, Equation (6) was applied to a large tract of irrigated land in Idaho, USA.

Description of study area

The Eastern Snake River Plain includes approximately 800,000 hectares of irrigated land on a plain that lies between 42 and 45 degrees north latitude, and between 111 and 115 degrees west longitude. Elevation ranges from approximately 800 meters above sea level in the southwest to 2000 meters above sea level in the northeast. Precipitation is in the range of 0.3 meter per year, with crop ET requirements in the range of 0.5 to 1.2 meter (Johnson et al, 1999). Virtually all crop production (alfalfa, small grains, potatoes, sugar beets, maize, dry beans and pasture) is irrigated.

Data

Crop mix and spatial location of crops were obtained from geographical information systems data (US Department of Agriculture, 2011). Soil depths and rooting depths allowed calculation of the fraction of wintertime precipitation available for summertime crop growth, in order to calculate rain-fed ET. Precipitation data were from Oregon State University (2011) and generalized soil depths from US Geological Survey (Garabedian, 1992). University of Idaho (2009) provided evapotranspiration data and US Department of Agriculture (2010) provided crop yield and price data. Values for parameter Z were subjectively estimated and ranged from 0.05 for pasture to 2.0 for potatoes.

Because the primary purpose was to test the assertion that consumptive use would increase with technology and/or management improvements, data collection and estimation were not particularly refined. Consequently, the differences between the B = 0.60 and B = 0.80 results will be meaningful, but absolute results at either value will be less so. The same crop mix, irrigated lands, commodity prices and full-irrigation yields were used for both simulations.

Calculation

Equation (6) was solved for approximately 900,000 sample points, each representing 0.9 hectares of irrigated crop. Willingness to pay and ET depth (consumptive use) from irrigation were calculated at one-millimeter irrigation depth increments. For each sample point, willingness to pay and ET values were written to a temporary table, from which demand and ET volumes were interpolated at a schedule of pre-determined prices and written to an output file. At each price, the quantity demanded and ET were summed over the region.

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[5] This assumes that fallow is an acceptable rotation crop for the high-revenue crop. If not, the high-revenue crop and its rotation partner can be treated as one crop with weighted-average yield, price and water-use parameters.

Results

Figure 7 shows the aggregate short-run demand for applied irrigation water (Iv, volume of applied irrigation water, versus Rv', willingness to pay per water volume) for the two levels of parameter B (consumptive-use fraction of field-applied water at full irrigation). As expected, at low marginal costs of water, the lower-B curve shows willingness to purchase significantly more water than the higher-B curve. At very high marginal costs, the lower-B curve goes to zero volume more quickly than the higher-B curve, again matching expectations.

Figure 7 is consistent with two informal observations in the Eastern Snake Plain. In much of the plain, canal users are charged an annual assessment on a per-hectare basis. The short-run marginal irrigation costs are energy and labor, typically summing to less than \$30 per 1000 m^3. At this range of marginal costs, Figure 7 indicates significant reductions in field-delivery volume when lower-loss technology is installed, matching observations. The second informal observation is that in areas of groundwater irrigation with high pumping lifts (approximately 150 meters), well-managed center pivots tend to have similar pumping volumes as systems with greater in-field losses, even though the higher-loss systems would be expected to need to pump greater volumes of water. This is consistent with the results in Figure 7 for costs greater than approximately \$30 per 1000 m^3.
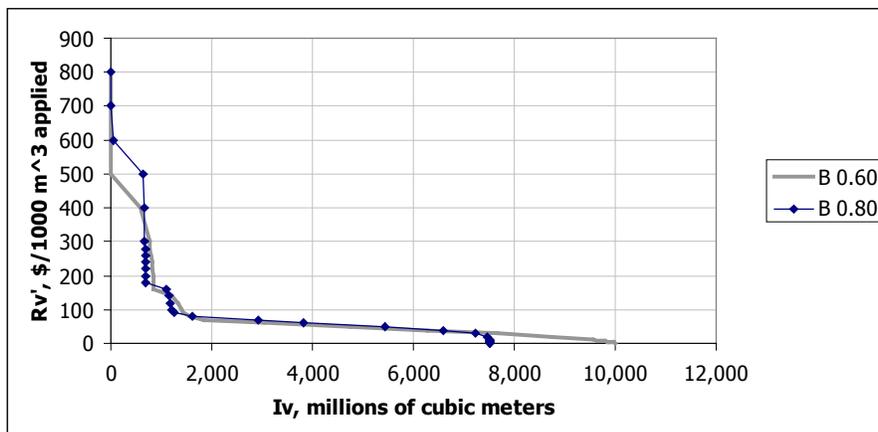

Figure 7. Aggregate demand for applied irrigation water across the entire Eastern Snake River Plain (Demande globale pour l'eau d'irrigation appliquée à travers la totalité de l'*Eastern Snake River Plain*).

At a marginal water cost of \$20 per 1000 m^3 with a full-yield consumptive-use fraction (B value) of 0.60, the field application is approximately 8.8 x 10^9 m^3, supporting 5.8 x 10^9 m^3 of evapotranspiration from irrigation. When the full-yield consumptive use fraction is 0.80, irrigation application at the same marginal cost drops by fifteen percent to 7.5 x 10^9 m^3 while consumptive use from irrigation increases by three percent to 6.0 x 10^9 m^3. This increase in consumptive use was obtained without increasing irrigated area, increasing evaporation relative to transpiration, explicitly increasing the number of irrigation events, changing the status-quo crop mix, or representing any difference in full-irrigation crop yield.

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4. DISCUSSION, CONCLUSIONS AND RECOMMENDATION

These results do not mean that improving irrigation technology and management is a bad idea. As explained by other investigators, there are many reasons to adopt high consumptive-use fraction irrigation technology (Perry, 2007; Ward and Pulido-Velazquez, 2008; Perry et al, 2009). The most important considerations have been well illustrated and explained. They include:

1) When the fate of the non-consumed fraction is some unusable sink, such as the ocean, a saline lake, or brackish groundwater, saving water through increasing the consumptive-use fraction of field-applied water does make additional supplies available for other uses (Huffaker, 2008).
2) When the status-quo fate of the non-consumed fraction is to support existing economic or ecosystem purposes, saving water does *not* make additional supplies available, it is simply an unintended reallocation.
3) Case-specific mechanisms often serve to increase consumptive use and reduce total basin supply when technology and/or management are improved. These can be significant in magnitude.

This paper's contribution is that even absent case-specific mechanisms, consumptive use is expected to increase. Equating marginal cost with marginal revenue product indicates the general result that reducing the non-consumed fraction of applied irrigation water (i.e. improving irrigation efficiency) will unambiguously increase consumptive use at all but the lowest marginal costs for water. This result is not dependent on the novelty of endogenously calculating crop price as a function of irrigation adequacy, nor upon increasing acreage or crop yield.

The important recommendations are that any proposal to improve irrigation technology or management must be accompanied by careful water budget analysis of the present-condition fate of the non-consumed fraction of applied irrigation water, and of the human and ecosystems made of the current waste stream. The analysis and plan must quantify the changes in rate, volume and timing of flows that will result from the improvement, both upstream and downstream of the irrigated parcel. Assignment of benefits and costs, and allocation of new fluxes made available, must be explicitly and unambiguously specified. Finally, an increase in consumptive use on the irrigated lands served by the improved system must be expected and considered in plans and analyses.

6. ACKNOWLEDGEMENTS

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