Impacts of irrigation efficiency improvement on water use, water consumption and response to water price at field level.

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Abstract

The potential rebound effect that can occur as a result of water-saving investments (or irrigation modernization) is receiving growing attention; paradoxically, although improved irrigation efficiency may reduce water use, it may also increase water consumption. This paper undertakes an analytical review of the microeconomic foundations of the effects of water-saving investments and the resulting irrigation efficiency on water use and consumption. Moreover, it analyses the relationship between irrigation efficiency, water demand and water pricing. Findings show that improving efficiency would significantly reduce water use, though the impact on water consumption would be negligible unless there was a radical increase in water cost. Thus, the potential rebound effect would not be related to irrigation efficiency, but rather to other factors such as irrigated area expansion, crop-mix changes, and market forces.

Keywords: water-use efficiency, water demand, water consumption, irrigated agriculture.

1. Introduction

The commonly-held belief that improving the efficiency of irrigation through high-tech agriculture would translate into water savings and a more sustainable use of the resource has been put in doubt by a wide variety of studies (see Levidow et al., 2014; Scott et al., 2014, among many others). Irrigation modernization, understood as the enhancement of the efficiency, flexibility and reliability of irrigation through the transformation of water delivery and application systems, may have undesirable consequences in terms of an increase in the amount of water used and consumed, commonly known as the rebound effect. In our analysis, this rebound effect is defined as the paradoxical increase in water consumption resulting from the introduction of more efficient irrigation technology aimed at reducing water use.

The European Commission (2012) has recently identified a potential rebound effect in irrigation water-saving measures and has stipulated that subsidies should be granted for water-saving investments that explicitly devote at least 50% of the 'water saved' to environmental goals (European Council, 2013). In recent years, the potential rebound effect resulting from water-saving investments is receiving growing attention in the academic sphere (Berbel and Mateos, 2014; Gómez-Gómez and Pérez-Blanco, 2014; Berbel et al., 2015). A recent FAO report (Perry et al., 2017) also questions the real water savings achieved by subsidizing the implementation of water conservation and saving technologies (WCSTs) in irrigated agriculture worldwide.

The Jevons paradox, as the rebound effect is also known, was first analysed in relation to energy consumption in the industrial sector (Jevons, 1865). In industrial production processes, however, the energy is fully consumed, which is not the case with the consumption of water in irrigation. The extracted water (or used water) ends up as: (1) beneficial evapotranspiration; (2) non-beneficial evapotranspiration; (3) non-recoverable runoff/percolation; and (4) recoverable runoff/percolation (Burt et al., 1997). The first three components constitute the consumed or depleted fraction, meaning that this water is not available for further use as it is consumed as evapotranspiration, incorporated into a product, or flows to a location where it cannot be readily reused (e.g., heavily saline water). The fourth component of the water abstraction (water use) is not consumed and is recoverable for further/later abstractions. Thus, an increase in irrigation efficiency may reduce water use, but paradoxically (in a Jevons sense) may also increase consumptive water use (Scheierling et al., 2006; Jensen, 2007; Ward and Pulido-Velázquez, 2008; Rodríguez-Díaz et al., 2012; Pfeiffer and Lin, 2014, among others). This controversial question is the focus of the present research.

Some authors have concluded that an increase in irrigation efficiency may necessarily lead to a rebound effect (in the sense of the Jevons paradox), but it has been difficult to build a methodological framework to explain it, and therefore, to predict the impact that an increase in the irrigation efficiency may have on water use (i.e. abstraction) and water consumption. Following the studies of Gómez-Gómez and Pérez-Blanco (2014) and Berbel and Mateos (2014), this work examines the microeconomic foundations of the effects of WCST investments and the associated irrigation efficiency, addressing water use and consumption separately, as they are not equivalent. Moreover, we analyse the relationship between water demand, water pricing and efficiency. After presenting the analytical framework in the next section, Section 3 analyses the links between irrigation efficiency, water use and water consumption. A brief discussion on the findings and their policy implications is offered in Section 4. Finally, some concluding remarks are summarized in Section 5.

2. Analytical framework: Efficiency, yield and relative irrigation supply

Following English (1990), irrigation water optimization may address three alternative criteria: when land is a constrained production factor but water is abundant, the farmer can either (a) maximize yield or (b) maximize profit per area; or when water is the limiting factor, (c) maximize profit by simultaneously considering land and water use. This research will focus on the 'limited land/unlimited water supply' case where land is a constraint and water is a variable input. Optimal solutions are shown in Table 1.

TABLE 1 HERE

where $Y(W)$ is crop yield as a function of applied water; Z represents a profit function when land is limited; P_y is crop price; CF is fixed costs; P_w is water price/cost; W is water applied.

According to overwhelming evidence from empirical research, the yield (Y) response to crop evapotranspiration (ET) may be expressed as in Doorenbos and Kassam (1979), which has been widely adopted in the agronomic literature as a general description of crop yield response to irrigation:

$$\left(1-\frac{Y}{Y_m}\right)=K_y\left(1-\frac{ET}{ET_m}\right) \tag{1}$$

where Y is actual crop yield; Y_m is the maximum crop yield for the crop in question; ET_m is maximum evapotranspiration; and K_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration. Furthermore, ET can be calculated as:

$$ET = R + (E \cdot W) \tag{2}$$

where R is the effective rainfall plus the variations in soil water storage during the crop growing cycle, W is the applied water, and E is the irrigation efficiency. Irrigation efficiency is defined as the water stored in the soil ready to be evapotranspired by the crop divided by the applied water ($E = (ET - R)/W$). It should be noted that, contrary to what is often believed, efficiency (E) is not a constant value but rather a variable function of the water applied, the crop ET and the effective rainfall (R). Equations (1) and (2) are combined to give the following equation:

$$\left[1-\frac{Y}{Y_m}\right] = K_y \left[1-\frac{E \cdot W + R}{W_m + R}\right] \tag{3}$$

where W_m is the net irrigation water requirements for a maximum yield (i.e. $W_m = ET_m - R$).

Equation (3) may be rewritten in terms of non-dimensional variables:

$$y = \frac{Y}{Y_m} = 1 - K_y + K_y \frac{r + E \cdot v}{1 + r} \tag{4}$$

where y is the ratio Y/Y_m, r the ratio R/W_m, the contribution of rainfall plus soil storage to the net irrigation requirements, and $v = \frac{W}{W_m}$ is the ratio of irrigation supply to maximum net irrigation needs. Hereafter, we also refer to the non-dimensional variable relative irrigation supply (v) as ‘water use’. This variable is defined as the ratio of applied irrigation water (W) divided by (W_m), which is the net irrigation required to achieve the maximum yield (Y_m) when we have 100% irrigation efficiency $(E_0 = 1)$.

As mentioned above, irrigation efficiency is not a constant value, and depends on the applied water. The ‘standard’ efficiency value for the different irrigation technologies found in the literature, which we denote by E_0, usually ranges from 0.6 for furrow irrigation to 0.95 for drip irrigation. By definition, it can be seen that E_0 is the ratio between the agronomic parameter W_m (irrigation needs for Y_m and $E_0 = 1$) and the water supply (W) required to achieve maximum yield (Y_m) for a given irrigation technology:

$$E_0 = \frac{W_m}{W} \tag{5}$$

Fig. 1 shows the yield-water response function, measured as the relative yield in relation to irrigation supply 'v' for different irrigation systems (i.e. furrow, sprinkler and drip irrigation) for a crop with a K_y of 1.25 (typical of maize), according to the model developed by Berbel and Mateos (2014) and based on Wu (1988) and English, et al. (2002). All simulations shown in the figures presented below have been performed taking $r = R/W_m$ equal to 0.2 (also typical of maize in a Mediterranean climate). Implicit in this value is the fact that the analysis refers to crops that use both rain and irrigation water, with the latter in greater proportion (this is typical of water-stressed locations). As discussed above, E_0 has been set to the typical efficiency values of 0.6 (furrow), 0.8 (sprinkler) and 0.95 (drip). Fig. 1 shows that as the value of E_0 increases, the response function shifts increasingly upwards and the drawn curve seems to shorten. For example, it can be seen that in order to achieve maximum crop yield, water supply must reach a value of v = 1.67 (circle in Fig. 1) in the case of a furrow irrigation system.

FIGURE 1 HERE

Following Berbel and Mateos (2014), Fig. 2 shows the relationship between efficiency E and relative irrigation supply v. For deficit irrigation practices with low values of v (that is, for $v \leq 0.76$, denoted by a circle in Fig. 2), it can be seen that efficiency (E) equals 1 for all irrigation systems used. Thus, when deficit irrigation is involved, crops take better advantage of irrigation water used, increasing efficiency. In other words, when the supply of irrigation is low (below the level of maximum yield), all the applied irrigation water is used by the crop for evapotranspiration, obviously with a yield below the maximum level.

FIGURE 2 HERE

Berbel and Mateos (2014) demonstrate that efficiency is determined by two variables: the technological efficiency at maximum yield, or standard efficiency (E_o); and the relative irrigation supply (v), as shown in equation (6):

$$E = \frac{(E_0 v + 1)^2 - 4\, v}{4(E_0 - 1) \cdot v^2} \qquad (6)$$

As illustrated in Fig. 2, this equation shows that for very low values of v , such as $v = 1/(2 - E_0)$, unitary efficiency (E=1) is easily reached. On the other hand, maximum yield is reached for each system at $v = 1/E_0$ (as can also be easily observed in Fig. 1 and 2). Thus, if irrigation is applied over the level of maximum yield, there is a steady decline in efficiency as the excess water is 'lost' at field level, mainly through returns to the river basin, aquifer or any other destination. The parameter E_0 in our model is equivalent to the parameter 'a' in the model of English (1990), which serves as an indicator of water distribution uniformity on the plot. For reasons of convenience, we decided to use the label E_0, as the value is equal to efficiency at maximum yield (generally used as the standard efficiency for the system) and this paper is focused on the economic implications of water use and water consumption as a function of efficiency and water pricing, as will be discussed in next section.

Having addressed the relationship between efficiency and relative irrigation supply, the following section aims to illustrate the relationship between water use (abstraction) and water consumption ('blue water ET') and irrigation efficiency. Traditionally, economic models analysing irrigation decisions are usually based on certain assumptions that may differ from the real world. The relevant features that such models should consider are:

- The linear nature of the yield-water relationship for low values of relative irrigation supply (v). The linear relationship holds for values of $v < 0.76$ for furrow irrigation or $v < 0.95$ for drip irrigation (solving the equation $v = 1/(2 - E_0)$ in equation 6).

- Once this point (unique to each irrigation system) has been surpassed, efficiency (E) steadily declines. When the maximum yield is reached (at $v = W_m/E_0$) the standard efficiency for each system determines the level at which irrigation should be stopped, as any water applied in excess of this level has zero marginal productivity (represented by a circle in Fig. 1 for the furrow irrigation system).

As we mention previously, most of the economic models dealing with irrigation efficiency usually erroneously assume a continuous and derivable water supply-yield relationship and a constant efficiency value, even though neither are realistic assumptions, as we have demonstrated above. The next section explores farmers' profit maximizing behaviour by introducing prices and costs into the analysis.

3. Efficiency, water use demand and water consumption

In order to analyse the implications of irrigation efficiency under the assumption of profit maximizing behaviour, price and cost variables will be included in the model. This is done by maximizing the following profit function:

$$Z = P_Y Y - P_W W - CF \tag{7}$$

where $P_Y Y$ represents the production value, $P_W W$ represents the total cost of water used, and CF is the total crop costs (which are assumed to be fixed). English (1990) proposes that variable costs (marginal fertilizer, etc.) can be included in the water price term (P_W), and we follow this suggestion. In any case, most of the costs are fixed and included in *CF*.

Farmers can be assumed to be price-taking firms, and consequently economic theory predicts that the optimum decision lies at the stage of the production function where both average and marginal products decrease. This condition also holds for our production function (with irrigation water as the input), from the very early stages of deficit irrigation to the maximum yield. By integrating equations (4) and (6) with equation (7), we can determine the optimum value for water use under unlimited water supply. This is found by solving the following derivative:

$$\frac{\partial Z}{\partial W} = 0 \tag{8}$$

The critical variables that determine optimal water use are: Y_m, maximum crop yield; K_y, the proportionality factor between relative yield loss and relative reduction in evapotranspiration; W_m, the net irrigation requirement for maximum yield; and E_0, the efficiency at maximum yield. Furthermore, it can be assumed that the ratio of water cost $(P_w \cdot W_m)$ to total income $(P_y \cdot Y_m)$ in normal conditions varies from less than 1% (intensive high-productivity crops) to a maximum of 20% (for some extensive crops).

Therefore, following Berbel and Mateos (2014), equation (8) is solved as:

$$v_{opt} = \sqrt{\frac{K_y}{[4(1 - E_0) \cdot (1 + r)] \left[\frac{P_w \cdot W_m}{P_y \cdot Y_m}\right] + K_y \cdot E_0^2}} \tag{9}$$

where the optimal relative water supply v_{opt} can be expressed as a function of the crop response to water, K_y, the contribution of rainfall plus soil storage to the net irrigation requirements r, the value of the $\frac{P_w \cdot W_m}{P_y \cdot Y_m}$ ratio, and the efficiency E_0. Thus, the optimal level of relative water supply is not related to the fixed cost.

According to Gómez-Gómez and Pérez-Blanco (2014), an answer to the key question regarding the existence of a possible rebound effect resulting from the implementation of more efficient irrigation techniques can be found in the behaviour of the derivative of water use (ν_{opt}) with respect to changes in efficiency. Fig. 3 illustrates the response of water use to an increase in water price, integrated as the ratio of water cost to crop income $\left(\frac{P_w \cdot W_m}{P_y \cdot Y_m}\right)$.

FIGURE 3 HERE

The slope of the response function decreases when efficiency improves, as Fig. 3 illustrates. This is shown as the lines representing each irrigation technology — 0.60, 0.80 and 0.95 for furrow, sprinkler and drip irrigation, respectively — become more vertical. Water consumption (ET) is a fraction of water use (W), with the excess water 'lost' as return flows leave the farm. Water consumption and water use are both relevant parameters in farmer decision-making and irrigation technology. Furthermore, Fig. 3 shows that when the price of water is zero (fixed cost per hectare or from a very cheap source), the demand for irrigation water equals water use at maximum yield, defined by the inverse value of efficiency at maximum yield ($\nu_{opt} = 1/E_0$). Consequently, the good news is that for low values of water price, the water-use savings are substantial when efficiency changes from E_0= 0.6 (i.e. traditional furrow) to highly-efficient irrigation technology (i.e. drip, with E_0= 0.95). Thus, there is plenty of room for improvement in the 'water use' indicator. Unfortunately, this good news carries with it some bad news; namely, that the elasticity of water use demand decreases when efficiency improves, which would imply that water-pricing policies would be ineffective at managing water demand when irrigation efficiency (E_0) is high (see Berbel and Gómez-Limón, 2000 and elsewhere).

The impact of water price on water use (W) and water consumption (ET) when technology changes from furrow (E_0= 0.6) to drip irrigation (E_0= 0.95) is shown in Fig. 4. The response of water use to water price is wider than the response of water consumption, as illustrated by the slope of the curves. Water consumption or ET is considered the relevant variable in agronomy and hydrology, as it represents the unrecoverable part of the total amount of water used for irrigation.

Specifically, Fig. 4 shows estimates of four response functions: the continuous lines on the right are the water use functions for two irrigation systems, furrow irrigation (E_0 = 0.60) and drip irrigation (E_0 = 0.95), while the dashed lines on the left are the estimates of the water consumption functions. The distances A-A', B-B' and C-C' represents the 'return flows' (or non-consumed fraction of used water). A substantial reduction in return flows can be seen as efficiency increases.

FIGURE 4 HERE

A change of irrigation system from furrow (A/A') to drip irrigation (C/C') is illustrated in Fig. 4, along with a hypothetical increase in water cost. The critical question now arises when the ratio $\frac{P_w \cdot W_m}{P_y \cdot Y_m}$ varies. Most authors have found an increase in water cost (e.g. more energy consumption, equipment maintenance, etc.) when WCSTs are implemented (Gómez-Gómez and Pérez-Blanco, 2014; Berbel et al., 2015). In order to test this hypothesis and analyse in detail the water use and consumption response to water cost variations, Table 2 shows these responses to variations in the water cost ratio $\left(\frac{P_w \cdot W_m}{P_y \cdot Y_m}\right)$ ranging from null to 0.10 (a realistic range).

The impact of increased irrigation efficiency (as a result of a technological enhancement) shown in Fig. 4 is analysed in greater detail in Table 2.

TABLE 2 HERE

In a low water cost situation, such as $\frac{P_w \cdot W_m}{P_y \cdot Y_m} = 0.01$, a technological change from furrow (E_0=0.60) to drip (E_0=0.95) irrigation leads to a reduction in water use (abstraction) at the economic optimum from $v_A = 1.632$ (point A in Fig. 4) to $v_B = 1.052$ (point B). This transition from A to B implies a 35% decrease in water used, while the reduction in water consumption ($ET_B - ET_{B'}$) is negligible.

As discussed above, it would seem logical that modernizing the irrigation system would tend to entail an increase in water costs (compared to the traditional systems they replace, more efficient irrigation techniques usually lead to higher costs associated with energy consumption, support infrastructure, and operating and maintenance costs). If we assume that the water price ratio increases to $\frac{P_w \cdot W_m}{P_y \cdot Y_m} = 0.10$, there is a displacement along the demand curve (E_0=0.95) and a response to water cost where the optimal water use is reduced from B-C in water use and from B'-C' in water consumption (ET), as shown in Table 2. The technological change results in a 36.2% saving in water used compared to the previous situation, with an additional 0.4% as a result of the cost increase. Corresponding changes on the consumption side (ET) are negligible.

Based on the findings discussed above, it can thus be seen that an increase in irrigation efficiency would reduce water use, but the impact on water consumption would be negligible, even if there was a radical price increase (as shown in Fig. 4).

These findings would suggest that the potential rebound effect would not be related to an enhancement in irrigation efficiency, but to other variables, such as irrigated area expansion, crop mix intensification, market forces and agricultural policy. A common situation described by Perry et al. (2017) and Lecina et al. (2010) is one in which there are high conveyance losses and deficit irrigation before the WCST is implemented. Fig. 5 depicts the particular case of the effect of WCST implementation when the irrigation system in place prior to the change is deficit irrigation, i.e., when farmers apply, throughout the crop cycle, irrigation quantities below the total irrigation requirements for maximum yield.

Fig. 5 illustrates a low water supply where only 70% of irrigation needs are available at farm level. The farmer obtains a yield below the technical maximum and some return flows — the difference between applied and evapotranspiration water $(\nu_1 - ET_1)$ — leave the farm. In this illustrative case, farmers do not use less water because of high water prices, but because they simply do not have enough water, which is a common situation in arid and semi-arid regions. For this reason, the initial price ratio in Fig. 5 does not affect water use (the price ratio needs to reach $P_w W_m / P_y Y_m = 0.25$ to affect demand). Nevertheless, the curves are still useful in highlighting the relationship between water use and ET. When the WCST is implemented, even when the water price increases ($P_w W_m / P_y Y_m = 0.10$), the water used decreases but the final water consumption (ET_2) is higher than the initial one (ET_1), and return flows $(\nu_2 - ET_2)$ have dropped by nearly a quarter (the reduction in flows was 25%).

FIGURE 5 HERE

Fig. 5 also serves as an illustration of the low response to water pricing in deficit irrigated crops (de Fraiture and Perry, 2007; Expósito and Berbel, 2017) as the demand curve is vertical from Q_1 to v_1 and it is only when prices become disproportionately high (around 25% of crop income in this exercise) that the prices influence water demand.

4. Discussion

The implementation of WCSTs requires the installation of expensive equipment and entails higher operational costs (due to the additional energy required for pumping and applying water in the field). Though public policies regarding irrigation modernization appear to have a twofold objective —reducing water use without impacting agricultural incomes — the reduction of the initial investment costs to be assumed by farmers has not always been followed by a significant reduction in water use or a more sustainable use of the resource. This paper focuses on the effect of improving irrigation efficiency on two variables (or response functions, as analysed in previous section): water use and water consumption.

Gómez-Gómez and Pérez-Blanco (2014), among others, suggest that improving irrigation technology leads to a Jevons paradox and that, contrary to commonly-held beliefs, water availability will decrease; thus, the real outcome of the supposedly water-saving technologies will be to exacerbate the already unsustainable use of water. Assuming that land is a limiting factor, the model presented in this paper tries to answer the question: *what happens with water use and water consumption after an increase in irrigation efficiency?*

In this regard, our findings would suggest that an increase in irrigation efficiency (due to WCST implementation, e.g., a change from furrow irrigation to drip irrigation) would generate different responses in terms of water use and water consumption, thus creating a need for separate analysis of the two variables. Furthermore, irrigation modernization, or in other words, a change in the irrigation technology used, has relevant implications with respect to water cost changes and in particular cases such as in areas with widespread use of deficit irrigation techniques. Nevertheless, some discussion points may be highlighted regarding the following relationships:

a) Water use and consumption response to WCST implementation.

There is no consensus regarding changes in water use after WCST implementation. Perry et al. (2017) summarize some cases where water use increases, but most of these cases have two features in common: a) widespread use of deficit irrigation before the WCST implementation and b) an increase in irrigated area after the implementation. On the contrary, when there are restrictions on irrigated area and the Water Authority either totally or partially hoards the 'water savings' derived from irrigation modernization, evidence suggests a reduction in water use: Berbel, et al. (2015) report a case study in southern Spain where water use decreased by 25% after WCST implementation, while Fernández-García et al. (2014) and García-Mollá et al. (2013) report that water diversion (abstraction) was significantly reduced (by 25–45 %) as a result of WCST implementation. In this regard, our findings show that the two variables, water use and water consumption, show different responses to an improvement in irrigation efficiency.

b) Water cost and WCST implementation.

Additionally, the abovementioned authors also observe other effects such as a significant increase in water costs, mainly due to a 50–100 % increase in energy consumption compared to previous levels, as well as a significant increase in the productivity of land, labour and water. Furthermore, traditional systems use flat rate water tariffs (per area billing) whereas the new WCSTs incorporate water metering and volumetric billing so that the water cost variable depends on the amount used. Berbel, et al. (2015) report a case study in southern Spain where, after investment, the water cost in real terms went from 0.038 to 0.054 EUR·m^{-3} (+41%). According to our findings, an efficiency increase would reduce water use, but would have a negligible impact on water consumption unless there was a radical price increase that affected consumption (Fig. 4).

c) Elasticity of water demand after WCST implementation.

The estimated model shows that water pricing becomes less effective as efficiency increases because water demand becomes more inelastic (i.e. less responsive to water pricing). Consequently, the increase in irrigation efficiency and the expected subsequent increase in water cost would need to be addressed on a case-by-case basis. Some authors have claimed that water pricing is not an effective means of achieving sustainability under these conditions (Berbel and Mateos, 2014; Expósito and Berbel, 2017). Yet, even in this context, pricing can produce positive welfare outcomes when water price is set rationally and with the aim of achieving full cost recovery, and where the revenue may be used to fund activities such as ecosystem services (Gomez et al., 2017).

d) The Jevons Paradox in agricultural systems.

Some authors have developed models to determine the existence of the rebound effect, based on two assumptions: i) water costs fall following the implementation of WCSTs; and ii) irrigation efficiency is a constant (E_0) that depends on the irrigation system and is not related to the level of water use (Gómez-Gómez and Pérez-Blanco, 2014). According to our results, both assumptions seem to be wrong though they are frequently used to build models that apply the Jevons paradox (which is appropriate in an energy context where both assumptions hold) to the irrigation context, where these assumptions do not reflect the reality and complexity of agricultural systems.

e) When deficit irrigation is applied.

Our findings regarding the situation where deficit irrigation was previously used due to limited supply (as analysed in Fig. 5) may explain the empirical findings of Lecina et al., (2010) for the Ebro, where they detect an increase in ET after the modernization of the irrigation network, and also those of Molle (2017), who reports similar results for northern Africa. Perry et al. (2017) illustrate certain cases around the world where there has been a shift from low-intensity traditional irrigation systems to high intensity systems when WCSTs are implemented, thus increasing water consumption (ET). As we have mentioned previously, the European Council (2013) requires that water savings are split evenly between the farmer and the Administration when the modernization is subsidized. A similar rule applies in the case of the Murray-Darling Basin (Australia), where WCST implementation by Australian farmers is subsidized by the government (Grafton, 2017). In our opinion, such regulations may help prevent the intensification of crop plans and therefore the potential rebound effect.

5. Concluding remarks

The estimated responses of water use and water consumption to increases in irrigation efficiency show that these variables must be analysed individually. Furthermore, the analysis carried out in this paper demonstrates significantly different responses of water use and water consumption to changes in water price related to irrigation system efficiency, and under the assumption of limited land and unlimited water supply. Thus, our research findings are based on the assumption that water use savings as result of WCST implementation are not used to expand the irrigated area, whether because there are restrictions on new irrigated land for natural reasons (no more land available either technically or agronomically) or for institutional ones (prohibited by law). In fact, this is a common situation in many parts of the world, such as in Spain, where public subsidies for the implementation of WCSTs are granted with the provision that there will be no expansion in irrigated area.

When this condition holds and farmers behave as profit-maximizing individuals, our model predicts that water use (abstractions) will be reduced significantly as the efficiency of the irrigation system increases. Conversely, the impact on water consumption (ET) is negligible. Additionally, the response of water demand to water price becomes significantly more rigid as irrigation efficiency improves and consequently water pricing becomes less effective at reducing water use.

We believe that our conclusions shed some light on the implications of adopting irrigation technology with the aim of reducing water use. The paper contributes new analytical evidence to the debate around the potential and paradoxical rebound effect associated with irrigation modernization. Future research is needed in order to apply the analytical model proposed in this paper to complex irrigation systems including multiple crops, with the aim of assessing the impacts on water use and consumption of new, more efficient irrigation technology. Moreover, additional research is required for the case where water supply is a limiting factor and irrigable land is unlimited, which is particularly relevant in semi-arid regions around the world.

Glossary

ET: crop evapotranspiration

WCSTs: Water Conservation and Saving Technologies

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Table 1

Optimization problems and solutions.

Objective	Function to maximize	Solution
Max Yield (kg/ha)	$Y(W)$	$\frac{\partial y}{\partial W} = 0$
Max Profit (\$/ha)	$Z = \left[P_y \cdot Y(W) - (CF + P_w \cdot W)\right]$	$P_y \frac{\partial y}{\partial W} - P_w = 0$

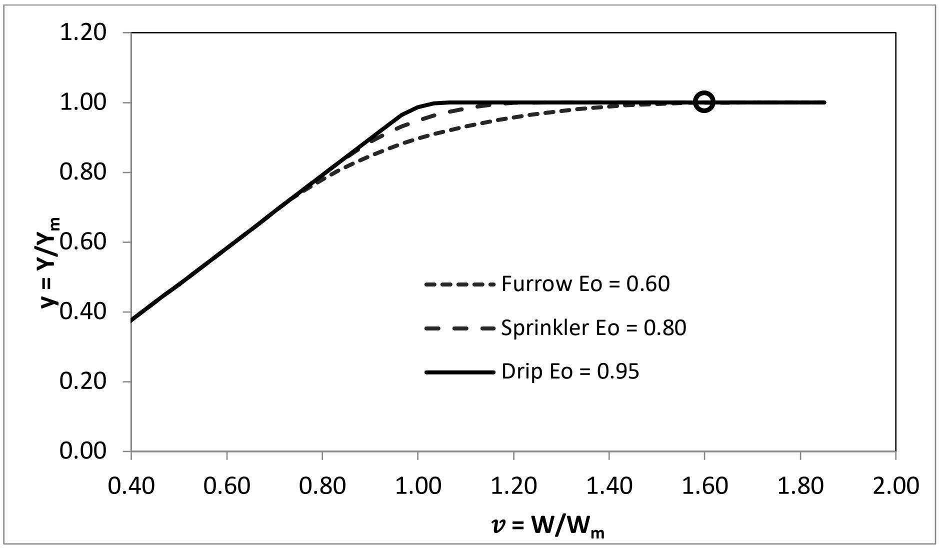
Source: Created by the authors, for a detailed explanation see Berbel and Mateos (2014)

Table 2

Optimal response of water use and water consumption to water cost

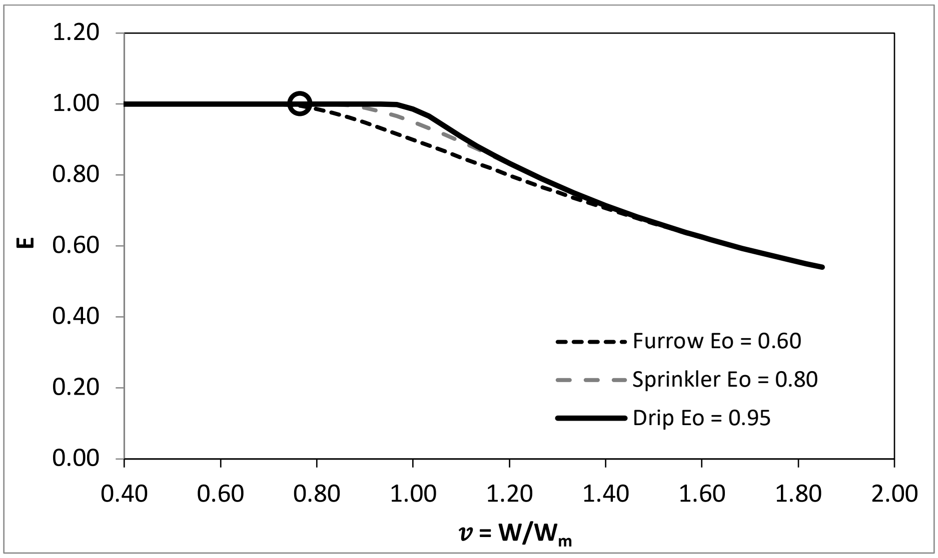
	$v = Water\ Use$		$ET = Water\ consumption$	
$\frac{P_w \cdot W_m}{P_y \cdot Y_m}$	E_0=0.60	E_0=0.95	E_0=0.60	E_0=0.95
0.00	1.667	1.053 ⇩	1.000	1.000 ⇩
0.01	1.632(A) ⇨	1.052(B) ⇩	1.000(A’) ⇨	1.000(B’) ⇩
0.05	1.513	1.047	0.996	1.000
0.10	1.395	1.042(C)	0.988	0.999(C’)

Note: K_y=1.25; r=0.2.



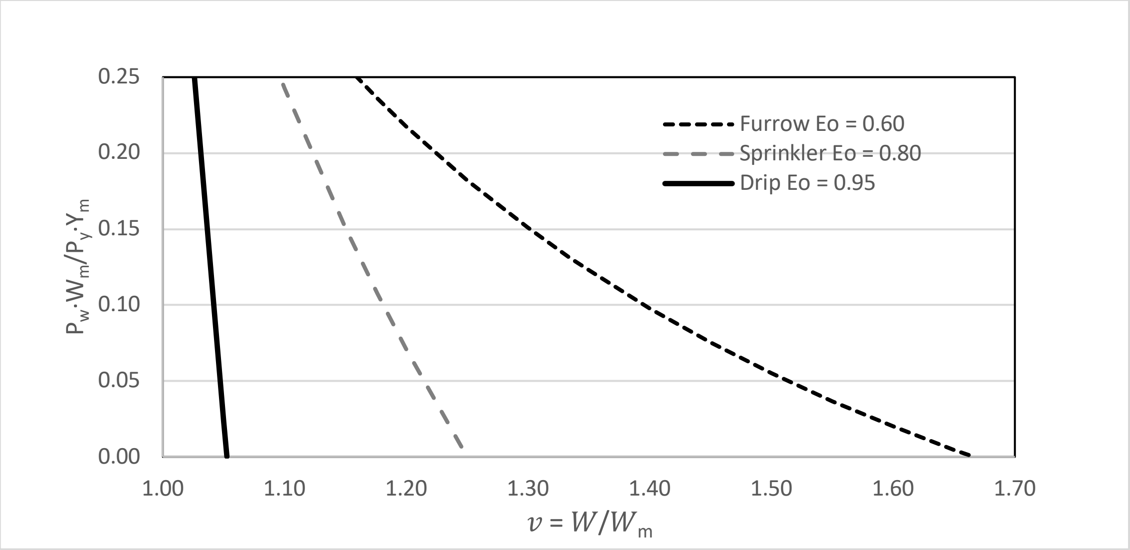
Example: For $K_y = 1.25$ and $r = R/W_m = 0.2$, when furrow irrigation is used ($E_0 = 0.6$), maximum yield is achieved for $v = W/W_m \geq 1.67$ (denoted by a circle in the figure).

Fig. 1. Relative yield response (y) as a function of relative irrigation supply (v) for a crop under different irrigation systems



Example: For $K_y = 1.25$ and $r = R/W_m = 0.2$, when furrow irrigation is used (E_0=0.6) and when $v = W/W_m \leq 0.76$ (denoted by a circle in the figure), the efficiency is (E=1)

Fig. 2. Response function between irrigation efficiency and relative irrigation supply (v) for a crop under different standard efficiencies (E_o)



Note: Typical technical efficiency values (E_0) of 0.60, 0.80 and 0.95. We have assumed that the ratio $(P_w W_m)/(P_y Y_m)$ is in the range [0 to 0.25].

Fig. 3. Response function between water cost-to-income ratio $(P_w W_m)/(P_y Y_m)$ and relative water supply $(v = W/W_m)$

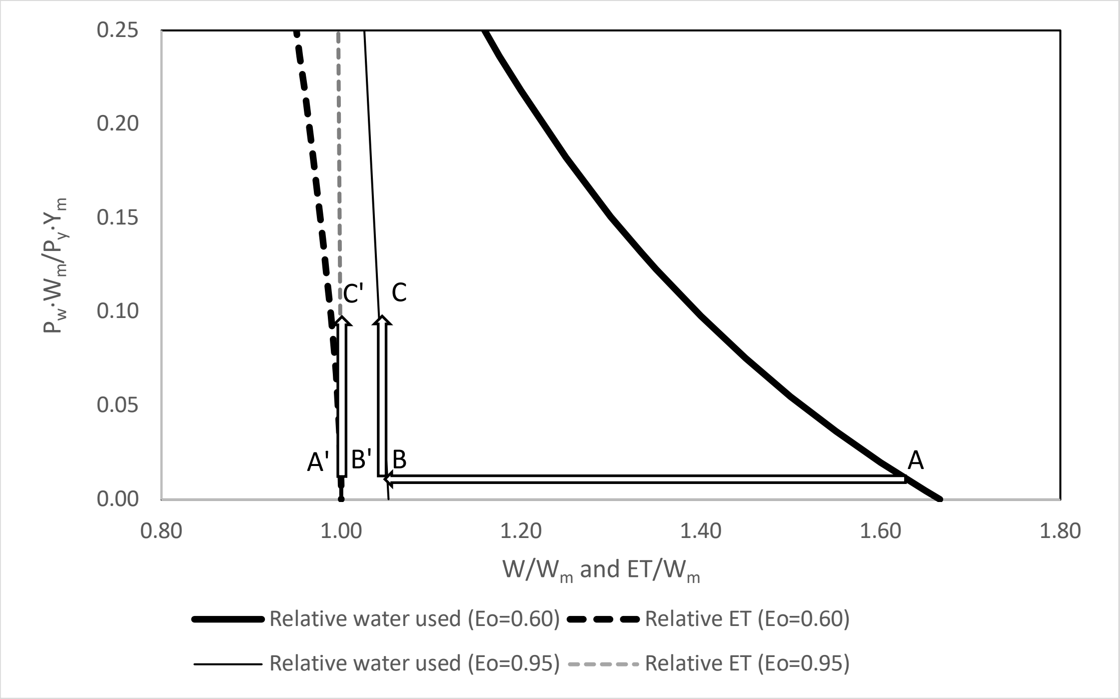


Fig. 4. Estimated response functions (demand curves) for water use (v) and water consumption (ET) to water cost.

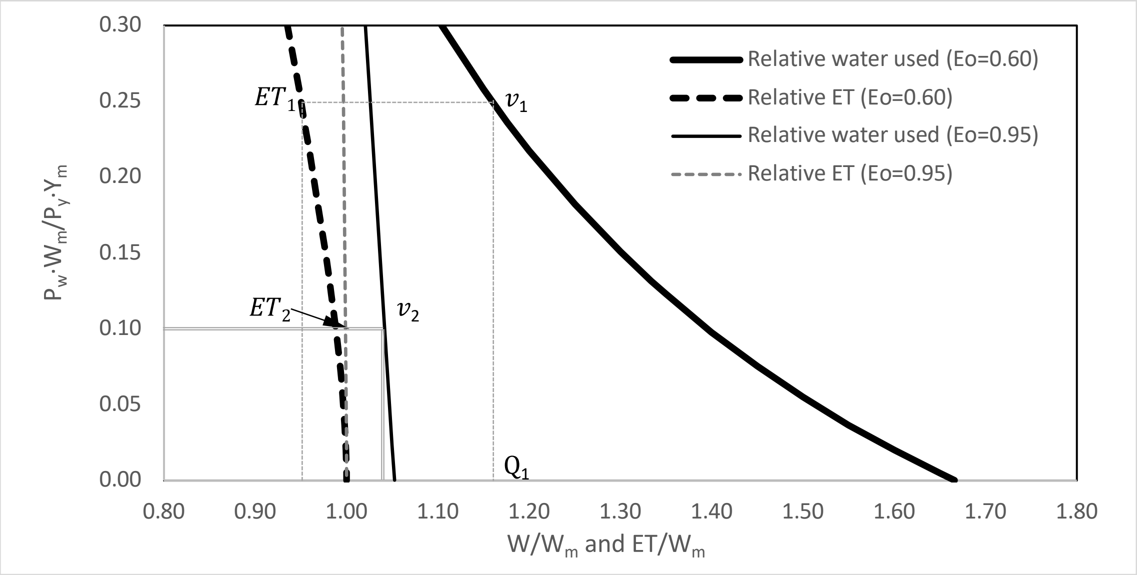


Fig. 5. Water use (v) and water consumption (ET) with deficit water supply before the WCST implementation. Q_1 = constrained water supply (70% of irrigation dose required for maximum yield for E_0=0.6); v_1= water use for E_0=0.6; ET_1= evapotranspiration for E_0=0.6; v_2= water use with WCSTs (E_0=0.95); ET_2= Evapotranspiration for E_0=0.95 with almost 100% irrigation needs.