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Microeconomic analysis of irrigation efficiency improvement in water use and water consumption[1]

Abstract

Increasing irrigation efficiency has been suggested as a solution in water scarce areas but its potential rebound effect (increased ex-post water consumption) is receiving growing attention; paradoxically, although improved irrigation efficiency may reduce water use, it may also increase water consumption. This paper presents a microeconomic analytical approach to assess the effects of water-saving investments and the resulting irrigation efficiency on water use and consumption at field level. 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 even if there is 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, which are out of the scope of this study.

Keywords: irrigation efficiency; water demand; irrigated agriculture; Jevons paradox; water conservation and saving technologies; water pricing.

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

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 (Adamson and Loch, 2014, 2017; Adamson et al., 2017; Connor et al., 2012; Levidow et al., 2014; Loch and Adamson, 2015; Molle and Tanouti, 2017; Perry et al., 2017; Scott et al., 2014). 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. Mateos and Araus (2016) review the strategies for engineering, agronomical, breeding and physiological pathways for the effective and efficient use of water in agriculture stating that engineering solutions for water conservation at farm level do not imply basin-scale water conservation. In the same line, Dumont et al. (2013) and Lopez-Gunn et al. (2012) evaluate the role of irrigation modernization questioning the reality of anticipated water savings whilst Molle and Tanouti (2017) show that, in the case of Morocco, implementation of drip irrigation tends to be associated with higher crop density, a shift to more water-intensive crops, and the reuse of 'saved water' to expand cultivated areas, resulting in higher water consumption. Studies such as Adamson and Loch (2014, 2017), Adamson et al. (2017) and Loch and Adamson (2015) analyse the potential adverse outcomes of irrigation modernization at a river basin scale (Australia's Murray-Darling Basin). These include reductions in environmental flows and obstacles to farmers' future capacity to adapt to climate change. Our analysis uses a microeconomic approach to analyse the impacts of irrigation efficiency enhancement on water use and water consumption at field (or plot) level. To the best of our knowledge, the analytical framework used in this study has not been attempted before. It should be remarked that there are other economic, social and agronomic implications at a larger scale of analysis (e.g. river basin scale) that can explain potential rebound effects in terms of water consumption, though these effects/implications are beyond the scope of this paper. 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 causes may be found at field level (the scope of this model), farm level (analysed with the help of mathematical programming methods such as in Gutiérrez-Martín and Gómez-Gómez, 2011) or at a larger scale, such as in the abovementioned references.

The European Commission (2012) has recently identified a potential rebound effect in irrigation water-saving measures as a relevant issue to account for 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). The decision to set 50% as the level of government appropriation of water savings is not based on a sound hydrological study and is defined at EU level; it would probably be worth conducting local-scale research to accurately determine whether this 50/50 public/private distribution is the appropriate level to achieve a satisfactory compromise between public, private and environmental goals. In recent years, the potential rebound effect resulting from water-saving investments is receiving growing attention in the academic sphere (Adamson and Loch, 2014, 2017; Berbel et al., 2015; Berbel and Mateos, 2014; Gómez-Gómez and Pérez-Blanco, 2014). A recent FAO report (Perry et al., 2017) also question the real water savings achieved by subsidizing the implementation of water conservation and saving technologies (WCSTs) in irrigated agriculture worldwide. Nevertheless, most of these studies focus on the effects of irrigation modernization (and the associated irrigation efficiency enhancement) on agricultural water use and consumption as a result of crop intensification, crop-mix changes, expansion of irrigated land, etc. As discussed above, our research objective is much less ambitious, as it focuses on the impacts of irrigation efficiency enhancement on water use and consumption at field level and excludes any other considerations. Furthermore, it uses a microeconomic approach to analyse how irrigation efficiency enhancement impacts water use and water consumption functions in terms of elasticity with respect to water cost changes. Additionally, this analytical approach allows us to discuss the effectiveness of water pricing measures as irrigation efficiency improves.

The Jevons paradox, as the rebound effect is also known, was first analysed in relation to energy consumption in the industrial sector (Jevons, 1865) and a majority of the existing empirical evidence shows that better (i.e. more efficient) technology does not necessarily imply less energy consumption and a cleaner environment (Alcott, 2005; Binswanger, 2001; Fisher-Vanden and Ho, 2010). In industrial production processes, however, the energy is fully consumed, which is not the case with the use of water in irrigation. The extracted water (or used water) ends up as: i) beneficial evapotranspiration; ii) non-beneficial evapotranspiration; iii) non-recoverable runoff/percolation; and iv) 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 (equivalent to the concept of 'water use' in this study, considering conveyance efficiency negligible for the sake of simplicity) is not consumed and is recoverable for further/later abstractions.

Thus, an increase in irrigation efficiency may reduce water use (abstractions), but paradoxically (in a Jevons sense) may also increase water consumption. According to some authors, the rebound effect is linked to WCSTs implementation (Jensen, 2007; Pfeiffer and Lin, 2014; Rodríguez-Díaz et al., 2012; Scheierling et al., 2006; Ward and

Pulido-Velázquez, 2008, among others). On the contrary, Huang et al. (2017) argue that using water-saving technologies at field level can reduce crop water use and improve the productivity of water. These different positions are not contradictory, because the effect at field level may differ from the effect at a larger scale, depending on the impact on return flows, non-beneficial evapotranspiration, the increase in irrigated land area, changes in the crop pattern or changes in agronomic practices. Water policy design should consider all these complex interactions to avoid the adverse outcomes of irrigation modernization (Adamson and Loch, 2017; Berbel and Mateos, 2014; Loch and Adamson, 2015).

Many authors have used case study analysis to affirm that an increase in irrigation efficiency will necessarily lead to a rebound effect (in the sense of the Jevons paradox). Dumont et al. (2013), Lopez-Gunn et al. (2012), and Molle and Tanouti (2017) analyse and describe this phenomenon. Furthermore, studies, such as Adamson and Loch (2014, 2017), Huffaker and Whittlesey (2000), and Ward and Pulido-Velázquez (2008) develop ambitious methodological frameworks to analyse the potential rebound effects at a river basin scale. Nevertheless, we believe that further microeconomic analysis of the effects of irrigation efficiency enhancement is required in order to better predict the impact on water use 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 increase in irrigation efficiency, addressing water use and consumption separately, as they are not equivalent. Moreover, we analyse the relationship between water demand (estimated as a response function of relative water use and consumption to changes in water cost) and irrigation efficiency, as efficiency enhancements affect water demand elasticity and thus, its responsiveness to water pricing measures. The analysis excludes any other side effects in the intensive or extensive margin, i.e. we do not account for crop-mix changes, irrigated area increases, or any other technical changes. 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 water use

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:

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

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:

$$ET = R + (E \cdot W) \qquad (2)$$

where R is the effective rainfall plus the variations in soil water storage during the crop growing cycle, W is the applied (or used) water, and E is the irrigation efficiency. Irrigation efficiency is defined as the maximum blue water[2] ready to be evapotranspired by the crop (total evapotranspiration less effective rainfall and soil water storage) divided by the used 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:

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

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:

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

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 (also known in agronomy as relative irrigation supply or RIS), defined as the used 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. As the word 'supply' may lead to a misunderstanding from a strict microeconomic point of view, we will refer to the variable 'v' as relative water use.

As mentioned above, irrigation efficiency is not a constant value, and depends on the used 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 (Berbel et al., 2015; Berbel and Mateos, 2014). By definition, it can be seen that E_0 is the ratio between the agronomic parameter W_m (irrigation needs for Y_m) and the water used (W) required to achieve maximum yield (Y_m) for a given irrigation technology:

$$E_0 = \frac{W_m}{W} = \frac{1}{v} \qquad (5)$$

[2] Blue water refers to agricultural water applied while green water refers to water from rainfall.

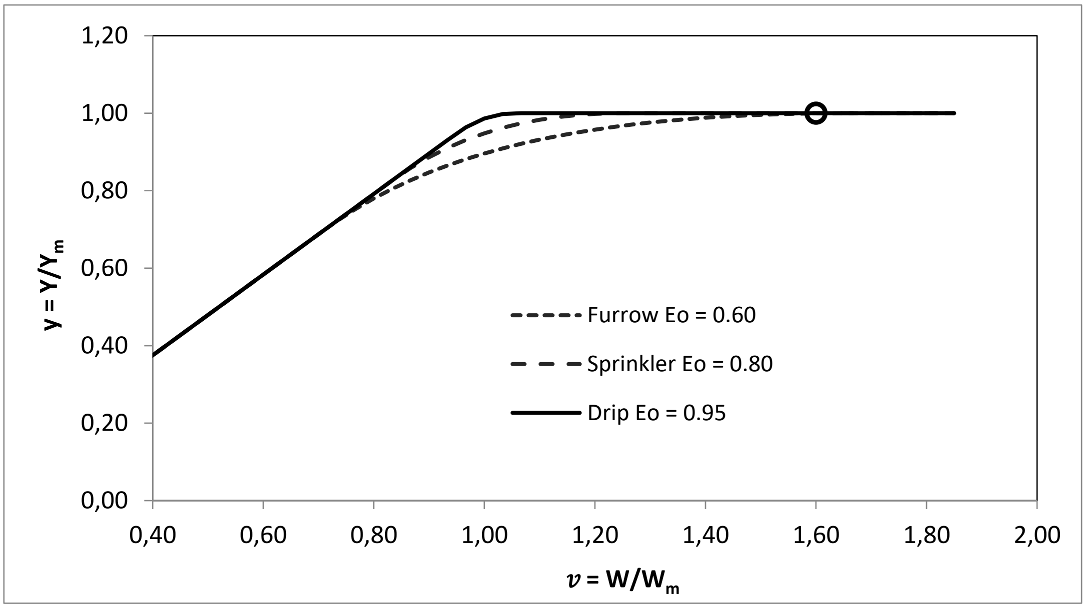

Fig. 1. Relative yield response (y) as a function of relative water use (υ) for a crop under different irrigation systems. Example: For $K_y = 1.25$ and $r = R/W_m = 0.2$, when furrow irrigation is used ($E_0 = 0.6$), maximum yield is achieved for $\upsilon = W/W_m \geq 1.67$ (denoted by a circle in the figure).

Fig. 1 shows the yield-water response function, measured as the relative yield in relation to relative water use (υ) 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). Although this study focuses on maize in a Mediterranean context, the proposed analytical framework can be used for other annual crops. All simulations shown in the figures have been performed taking $r = \mathrm{R}/W = 0.2$, so the represented crop receives 20% of its water requirements from usable rain and the rest need to be fulfilled by irrigation. This value is typical of a wide range of crops in different climatic conditions, including maize, but the model does not lose generality and any other rainfall contribution r may be simulated.

Additionally, 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 (which is also typical of water stressed locations such as Mediterranean regions). As discussed above, E_0 has been set to the typical efficiency values of 0.6 (furrow), 0.8 (sprinkler) and 0.95 (drip). These arbitrarily chosen values are selected for illustrative purposes only and should not be taken as representative of any specific location, although they may reflect the median values in some Mediterranean conditions, such as those in Andalusia (Consejería de Agricultura y Pesca. Junta de Andalucía, 2011). The parameters defined do not make the analytical model lose generality; the reader can modify the parameter in order to simulate any other local or technical conditions. 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 in the case of a furrow irrigation system, water supply must reach a value of v = 1.67 (circle in Fig. 1).

Following Berbel and Mateos (2014), Fig. 2 shows the relationship between efficiency E and relative water use v. For deficit irrigation practices (i.e. water used is reduced below maximum levels and yield stress is allowed with yield losses, what it is typical of water stressed locations) 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. In our case, deficit irrigation conditions refer to decreases in water used below economic optimal. 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 water is used by the crop for evapotranspiration, obviously with a yield below the maximum level.

Berbel and Mateos (2014) model define the efficiency as a function of two variables: the technological efficiency at maximum yield, or standard efficiency (E_0); and the relative water use (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 $v = 1/(2 - E_0)$, maximum 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 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 English (1990) model, which serves as an indicator of water distribution uniformity on the plot. For

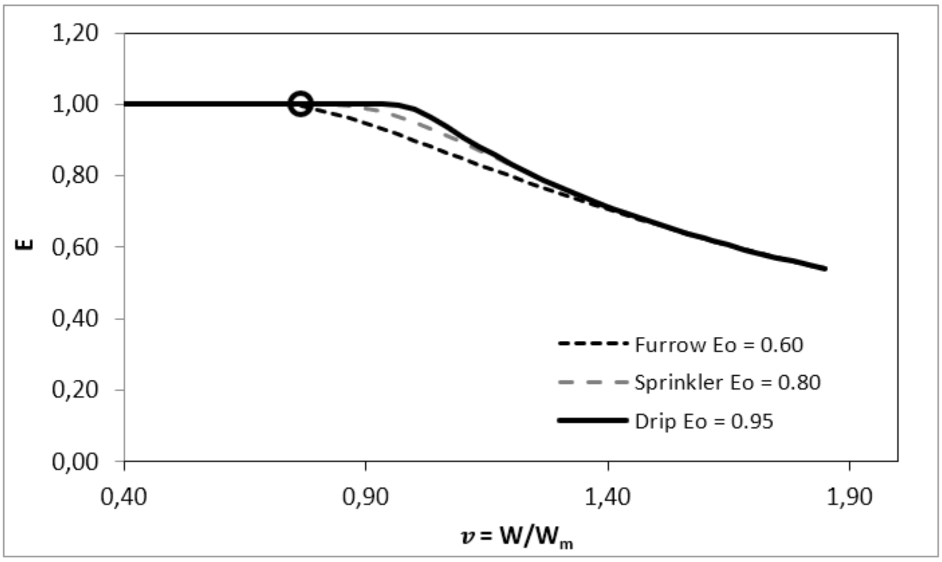

Fig. 2. Response function between irrigation efficiency and relative water use (v) for a crop under different standard efficiencies (E_o). Example: For $K_y = 1.25$ and $r = R/W_m = 0.2$, when furrow irrigation is used (E_0=0.6) and when $v = W/W_m \leq 0.76$ (denoted by a circle in the figure), the efficiency is (E=1)

reasons of convenience, we decided to use the label E_0, as the value is equal to efficiency at maximum yield (once again, 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, as will be discussed in next section.

Having addressed the relationship between efficiency and relative water use, the following section aims to illustrate the relationship between water use and water consumption (measured by blue water evapotranspiration in our study) 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 water use (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 use-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. This allows us to differentiate between water use and consumption (both measured in relative terms), and explore its relationship with irrigation efficiency.

3. Irrigation efficiency, water use and water consumption

Farmer irrigation water demand is subject to the behavioural assumption of profit maximization under the assumption that irrigated land is limited and there is enough water to reach full irrigation water supply (understood as water used or applied to the crop). This assumption implies that land is constrained and water is a variable input. 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:

$$Z = \left[P_y \cdot Y(W) - (FC + P_w \cdot W)\right] \tag{7}$$

where Z represents profit, $Y(W)$ is crop yield as a function of used water; P_y is crop price; FC is fixed costs; P_w is water price/cost; W represents water use. In economics, a production function relates physical output of a production process to the used physical inputs or factors of production. This definition applies to the production function $Y(W)$.

Following English (1990), variable costs (e.g. marginal fertilizer due to increased yield compared to rain fed) can be included in the water price term (P_W). In any case, and in order to isolate the role of used irrigation water as efficiency increases, all costs related to rainfed production may be included in the fixed cost term (FC) in our analysis. Farmers can be assumed to be price-taking individuals, 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:

$$\frac{\partial Z}{\partial W} = 0 \, ; \quad P_y \frac{\partial y}{\partial W} - P_w = 0 \qquad (8)$$

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 25% (for some extensive crops).

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

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

that corresponds to a water use curve with a parameterized P_w under *ceteris paribus* conditions and where the optimal of relative water use ν_{opt} can be

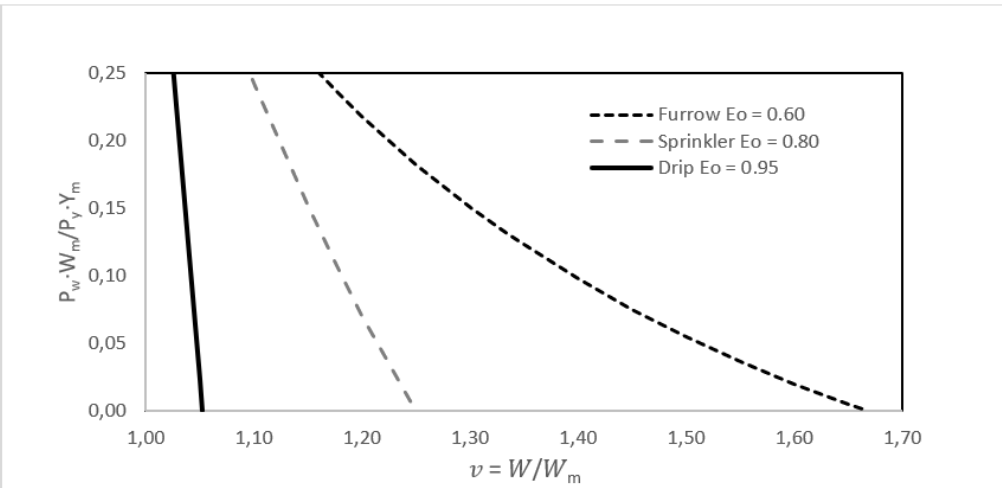

Fig. 3. Response function between water cost-to-income ratio $(P_w W_m)/(P_y Y_m)$ and relative water use ($\upsilon = W/W_m$). Note: The ratio $(P_w W_m)/(P_y Y_m)$ is usually in the range [0 to 0.25].

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 use is not influenced by 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 $\left(\frac{P_w \cdot W_m}{P_y \cdot Y_m}\right)$.

The slope of the response to water price function (as proxy of a water demand 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. Evapotranspirated water (ET) is a fraction of water use (W), with the excess water 'lost' as return flows leave the farm. Therefore, 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 (e.g. fixed cost per hectare or from a very cheap source), the 'demand' for used 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 amount of water used. Unfortunately, this good news carries with it some bad news; namely, that the elasticity of water use response function 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 for example Berbel and Gómez-Limón, 2000).

The impact of water price on water use (W) and water consumption ('blue water' ET), being both variables represented in relative terms (with respect to W_m) 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. This is relevant as water consumption 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 response 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 response functions. The distances A-A', B-B' and

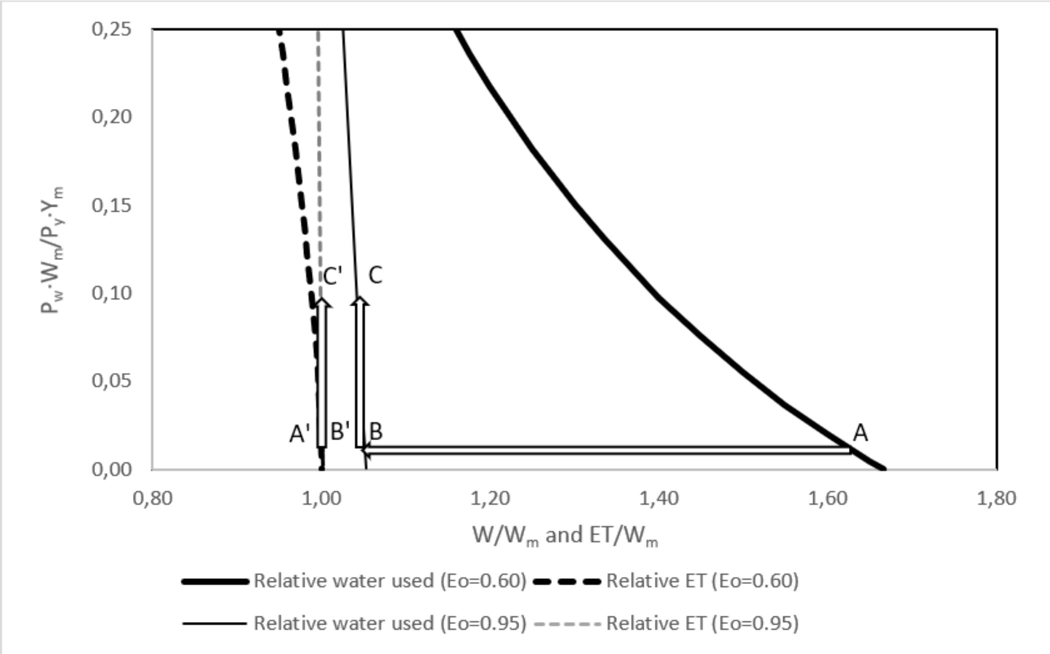

Fig. 4. Estimated response functions for relative water use (W/W_m) and relative water consumption (ET/W_m) to water cost ratio.

C-C' represent the 'return flows' (or non-consumed fraction of used water). A substantial reduction in return flows can be seen as efficiency increases.

A change of irrigation system from furrow (points A in water use and A' in ETP) to drip irrigation (C and C' respectively) is illustrated in Fig. 4, along with a hypothetical increase in the water cost ratio. 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 (Berbel et al., 2015; Gómez-Gómez and Pérez-Blanco, 2014). 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 0.01 to 0.10 (a realistic range).

The impact of increased irrigation efficiency (as a result of a technological

Table 2. Optimal response of relative water use and relative water consumption to water cost ratio

	Water use		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.

enhancement) shown in Fig. 4 is analysed in greater detail in Table 2.

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 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 (Fernández-García et al., 2014; Mushtaq et al., 2013; Rodríguez-Díaz et al., 2011). If we assume that the water cost ratio increases to $\frac{P_w \cdot W_m}{P_y \cdot Y_m} = 0.10$, there is a displacement along the response curve (E_0=0.95) as the optimal point is reduced from B to C in water use and from B' to C' in water consumption, as also 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 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 water cost 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 widespread deficit irrigation practices 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 irrigation supply where only 70% of irrigation needs are available at farm level (Q_1). The farmer obtains a yield below the technical maximum and some return flows — the difference between used and consumed water ($v_1 - ET_1$) — leave the farm. In this illustrative case, farmers do not use less water because of high water cost, 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 cost ratio in Fig. 5 does

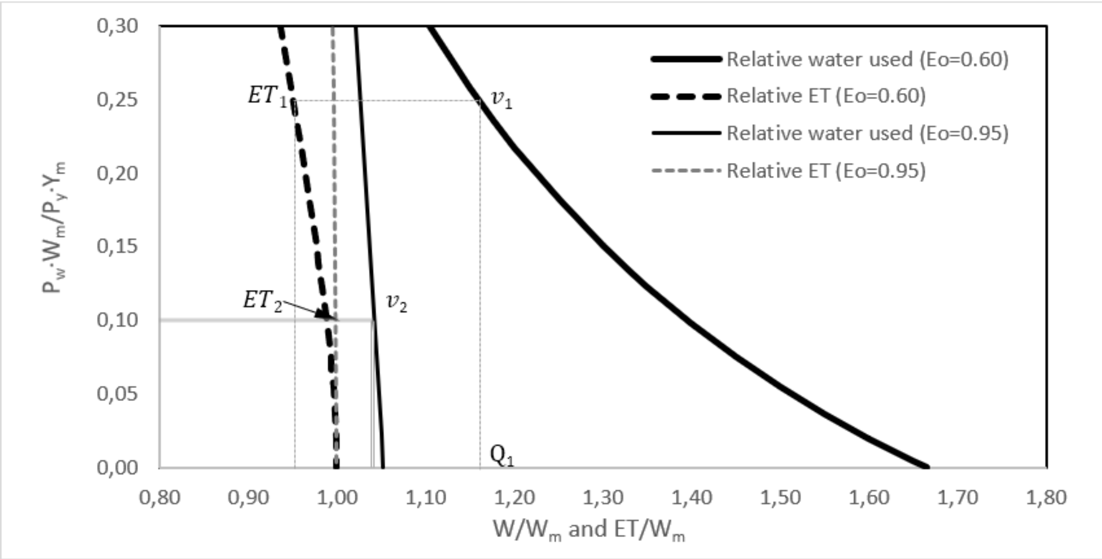

Fig. 5. Relative water use and relative water consumption with deficit water supply before the WCST implementation. Q_1 = constrained water supply (70% of irrigation dose required for maximum yield for E_0 = 0.6); υ_1 = relative water use for E_0 = 0.6; ET_1 = relative evapotranspiration for E_0 = 0.6; υ_2 = relative water use with WCST implementation (E_0 = 0.95); ET_2 = relative evapotranspiration for E_0 = 0.95.

not affect water use (the water cost ratio needs to reach $P_w W_m / P_y Y_m = 0.25$ to affect water 'demand'). Nevertheless, the response curves are still useful in highlighting the relationship between water use and consumption. When the WCST is implemented, even when the water-cost ratio 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 ($\upsilon_2 - ET_2$) have dropped by nearly a quarter (the reduction in flows was 25%).

Fig. 5 also serves as an illustration of the minimal 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 υ_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, for example, to the additional energy required for pumping and applying water in the field) (Khan et al., 2008; Mushtaq et al., 2013); this effect is acknowledged in Fig. 4 and Table 2. 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 (Loch and Adamson, 2015). This paper undertakes a microeconomic analytical approach to analyse the effects of improving irrigation efficiency on two variables (or response functions, as analysed in previous section): water use and water consumption.

Studies such as Gómez-Gómez and Pérez-Blanco (2014) and Adamson and Loch (2014, 2017) argue that improving irrigation technology leads to a Jevons paradox and that, contrary to commonly-held beliefs, water consumption increases, reducing water availability for other uses. Thus, the real outcome of the supposedly water-saving technologies will be to exacerbate the already unsustainable use of water. Under the considered assumptions, the microeconomic model presented in this paper tries to answer the question: *At field level, what happens with water use and water consumption after an increase in irrigation efficiency?*

Our findings 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 at field level, 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 certain features in common: a) a previous context of widespread use of deficit irrigation before the WCST implementation, b) an increase in irrigated area after the implementation, or c) significant intensification of farm crops (double cropping or increasing tree density). A sound water policy should take this evidence into account. Positive results in terms of a reduction in water use have been achieved when there are restrictions on irrigated area and the Water Authority either totally or partially hoards the 'water saving' derived from irrigation modernization. Evidence of this has been provided by Berbel et al. (2015), who report a case study in southern Spain where water rights 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 the same line, Huang et al. (2017) show that, in the case of North China, using WCSTs can reduce crop water use and improve the productivity of water. 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 (Fernández-García et al., 2014; Rodríguez-Díaz et al., 2011). 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 use and consumption response functions become more inelastic with respect to water cost (i.e. less responsive to water price increases). 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 certain conditions (Berbel and Mateos, 2014; Expósito and Berbel, 2017). Yet, even in these cases, pricing can produce positive welfare outcomes when water price is set rationally and with the aim of achieving a higher level of cost recovery; see Borrego-Marín et al. (2015) for a discussion on cost recovery levels under the Water Framework Directive in the EU.

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.

Furthermore, studies such as Adamson and Loch (2014, 2017), Adamson et al. (2017) and Loch and Adamson (2015) develop ambitious models to evaluate whether the expected water savings from irrigation modernization processes (and the associated irrigation efficiency enhancement) are real at river basin scale. These models are also aimed at analysing any adverse outcomes (e.g. reduction in return flows, impossibility of achieving environmental objectives, and farmers' increasing risk exposure to climate change due to changes in crop mix) arising if appropriate policy options are not taken. In this line, Huffaker and Whittlesey (2000) put forward a condition to guarantee basin-wide economic benefits based on actual, and not illusory, water savings. It consists in limiting efficiency investments to those that do not reduce appropriable return flows by downstream and instream uses. In addition, Ward and Pulido-Velázquez (2008) show that water conservation subsidies are unlikely to reduce agricultural water consumption at a basin scale. Regarding necessary policy measures to minimize rebound effects, they suggest a careful definition and administration of water rights, as well as an appropriate application of water accounting, water markets and transfers, defined in terms of water depleted rather than water applied. These conclusions are also supported by Berbel and Mateos (2014) regarding the need to control irrigated area expansion and the allocation of water-use savings. The microeconomic approach used in this study does not aim to account for these issues, as they appear at a larger scale of analysis (e.g. river basin scale).

e) When irrigation water supply changes from 'deficit' to 'full' irrigation after WCSTs implementation.

When deficit irrigation is dominant in the previous situation due to limited water resources (as analysed in Fig. 5) the proposed microeconomic model at field level may illustrate the empirical findings of Lecina et al. (2010) for the Ebro, where they detect an increase in water consumption after the modernization of the irrigation network, and also those of Molle and Tanouti (2017), who report similar results for northern Africa. FAO report by Perry et al. (2017) discuss 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. As we have mentioned previously, the Administration may require that water savings are split evenly between the farmer and the public domain 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, although such regulations may help prevent the intensification of crop plans and therefore the potential rebound effect, they need to be complemented with further policy measures (as those argued by Adamson and Loch, 2017; Huffaker and Whittlesey, 2000; Ward and Pulido-Velázquez, 2008) in order to guarantee real water savings at a river basin scale.

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 cost related to irrigation system efficiency. 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 technically available) 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. But the use of 'anticipated water savings' to enlarge irrigated area or to intensify significantly the farm is the explanation of the observed rebound effect that we have mentioned in the literature (see Molle, 2017; Perry et al., 2017; van der Kooij et al., 2017, to quote some recent examples).

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

The proposed microeconomic model has several limitations as it is focused on field level response and assumes certainty, profit-maximizing farmer behaviour and restrictions on irrigated land expansion. Nevertheless, the model results shed some light on the implications of adopting irrigation technology with the aim of reducing water use at field level. In this sense, the paper adds new analytical evidence to the debate around the potential and paradoxical rebound effect associated with irrigation modernization. Future analytical models should include multiple crops and whole-farm decision-making (which should form the basis for more complex and comprehensive basin models). This will allow more realistic bottom-up models aimed at evaluating the impacts of new, more efficient irrigation technology on water use and consumption. Moreover, additional research is required for the case where irrigation 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.

RIS: relative irrigation supply.

Water Consumption (in relative terms): irrigation water consumed divided by the net irrigation required to achieve the maximum yield.

Water Use (in relative terms): irrigation water used (applied) divided by the net irrigation required to achieve the maximum yield.

WCSTs: Water Conservation and Saving Technologies

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