The Pitfalls of Efficiency in Irrigation Modernization

by

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Abstract

Increasing efficiency in resource use is a commonly accepted aim. It creates the possibility of solving the economic problem of scarce resource allocation in a way that generates more income and, potentially, increases welfare. However, it has long been clear that higher levels of efficiency in the use of specific resources do not necessarily lead to proportional increases in resource conservation, since there are rebound effects in consumption. Efficiency improvements might even encourage additional resource use, a situation known as backfire. Moreover, the existing literature covers specific resources, mainly energy and water, separately. In this paper we present a dynamic model of irrigation where efficiency in water use is considered, and we highlight the role played by energy use through pumping costs.

Keywords: Irrigation; Water-use Efficiency; Energy Use; Renewable Energy;

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1. Introduction

The word “efficiency” carries a positive tone in various contexts, from academia to policy. When applied to natural resource use, where scarcity constraints are increasingly recognized as a barrier to sustainability, eco-efficiency sounds like a winning proposition that everyone can agree with. A glowing example can be found in the Roadmap to a Resource Efficient Europe (EC, 2011, p. 3), which states: “Resource efficient development... allows the economy to create more with less, delivering greater value with less input, using resources in a sustainable way and minimizing their impacts on the environment.” Nevertheless, the pitfalls of relying on efficiency to reduce resource consumption have been pointed out in the literature at least since the 19th century (Jevons, 1865). User decisions will adapt to circumstances: if a particular service requires less of a given resource, there might be an immediate decrease in use, but this can be partially or wholly overturned through various counteracting mechanisms that lead towards higher resource use.

Significant research has discussed efficiency and pointed out the possibility of rebound effects, especially within energy economics, where efficiency is usually defined as the ratio of useful work to energy input. It is customary to organize rebound effects into direct, indirect, and economy-wide effects (Sorrell and Dimitropoulos, 2008), although alternative classifications are possible (Van Den Bergh, 2011; Gillingham, Rapson and Wagner, 2016). Van den Bergh, in particular, points out that energy efficiency gains can affect the use of other resources, whose use might increase in the process, a phenomenon he labels “environmental rebound”.

In the field of water economics, and for irrigated agriculture in particular, similar definitions of efficiency are common: if less water is applied for the same amount of water effectively consumed by crops, then irrigation efficiency can be said to have increased, although alternative definitions of efficiency exist (see Scheierling, Treguer and Booker, 2016, Table 1). Notably, this type of application efficiency is a focus of policy efforts to reduce water use in agriculture, such as those that have been put forth in Portugal and Spain in "irrigation modernization" programs (MAGRAMA, 2010; DGADR, 2014). However, in water an additional effect turns up: the part which is applied but not consumed is mostly not "lost" nor "wasted", since it will tend to percolate back to water bodies as return flow (Dumont, Mayor and López-Gunn, 2013). Moreover, erroneously perceived water "savings" from irrigation modernization are often used to justify the expansion of irrigated land, a particularly harmful development from a basin-wide perspective.[3]

Many papers uncover the issues surrounding irrigation efficiency goals, but most do so without considering the resource stock evolution. (Huffaker and Whittlesey, 2000) compare the actions of farmers along a river, who respond to individual incentives for improvements in their irrigation systems, to what would be optimal considering all users along a stream, highlighting the (economic) inefficiency of (technical) efficiency measures. Gómez and Pérez-Blanco (2014) identify the possible rebound effect of irrigation improvements in a static model when water prices are constant and note that the overall effect on water use might be positive or negative. (Ward and Pulido-Velazquez, 2008; Pfeiffer and Lin, 2014a, 2014b) provide further evidence, theoretical and empirical, of the potential pitfalls of irrigation technology improvements in terms of resource conservation, respectively in the Rio Grande and in western Kansas. Peterson

[3] In a recent example, the Portuguese Minister for Agriculture announced that improvements in the efficiency of irrigation in the Alqueva dam area (from an average application of 5000 m^3/ha to 3000 m^3/ha) will allow an expansion of the maximum irrigated surface from 120 000 ha to 167 000 ha. Water prices have also been lowered (20% to 33%), with additional discounts provided to farmers who connect to the irrigation system, see http://observador.pt/2017/03/14/preco-da-agua-do-alqueva-para-rega-baixa-entre-20-e-33/ .

and Ding (2005), while noting that the effect of efficiency improvements is in general ambiguous, find some evidence of a reduction in water use for an illustration in the High Plains. Huang, Wang and Li (2017) do find empirical support for a reduction in water use after water-saving technologies were implemented in a sample of villages in Northern China.

Quintana Ashwell and Peterson (2016) provide an analysis that explicitly incorporates the groundwater stock evolution as well as a labor-saving effect that is presumed to come with more efficient irrigation capital. Their simulation finds that water table height reaches a slightly lower value with irrigation capital subsidies relative to the myopic solution without technological improvement, albeit far below the social planner optimum. However, they find that the welfare gains (measured in terms of net farmer benefits) of the subsidy are relevant. Sears et al. (2018) summarize the existing literature on irrigation-efficiency incentive programs and again emphasize that they have not been effective in groundwater conservation. More generally, Berbel et al. (2015) review the literature on the rebound effect of water savings measures, highlighting the different results obtained in various conditions, and stressing the need for further research. In this line, and based on the evidence provided by various worldwide case studies, Grafton et al. (2018) outline a set of recommendations for irrigation policies to improve global water sustainability.

Finally, in a recent communication, Perez-Blanco (2017) summarized a sample of 236 papers dealing with water conservation technologies in irrigation and showed that while applied water did generally fall, consumed water did not, generating measurable harms in environmental flows. Farmer incomes tend to increase, but this should not be the sole measure of welfare guiding policy implementation.

In this paper, we present a theoretical model of groundwater management where improvements in water irrigation efficiency are included. We also remark on the threat of coupling the use of zero-marginal-cost renewable energy (such as solar panels) with highly productive irrigation systems based on deep wells, a trend that is appearing in many irrigation areas due to the lowering cost of solar panels and misguided subsidy policies.

The remainder of this paper is organized as follows. In Section 2, the intertemporal irrigation model with water-use efficiency is presented for both the myopic and the social planner's cases, and the results are discussed. Section 3 introduces renewable energy sources in water pumping, and finally, Section 4 adds some discussion on the topic.

2. The Model

We begin with a description of the theoretical setup for groundwater extraction for irrigation when water-use efficiency is considered. We compare the common property solutions with the optimal groundwater extraction, assuming that there exists a large number, n, of identical farmers pumping from an underlying aquifer.

Myopic Solution

In this case we assume that each firm does not take into account the impact of its pumping on the condition of the aquifer (myopic behavior). We distinguish between water taken from the aquifer, which is then applied to the land (assuming no conveyance losses), and water effectively used by crops.[4] Consider the representative farmer's groundwater-use decision problem on a single land-irrigated parcel in a given year. Let

[4] Scheierling et al. (2016) further distinguish water withdrawn from the source, water applied to the field, water consumed beneficially by crops, water consumed non-beneficially, for example through evaporation from the soil, and water returned to the environment.

$y_t(g_t;\theta)$ represent farm revenue, obtained from the use of a productive input, g_t, where $g_t = \varepsilon x_t$ stands for effective water at time t, $\varepsilon \in [0,1]$ denotes the (technical) irrigation efficiency, and x_t is the applied water, that is, the amount of irrigation applied to the field. Therefore, irrigation efficiency is defined as the proportion of applied water that is beneficially used by a crop (Burt et al., 1997), that is, the proportion of irrigation which is not lost to evaporation or run-off and reaches the crop root area. Moreover, θ stands for a vector of parameters that may influence farm productivity.

We assume that $y_t(g_t;\theta)$ is increasing and strictly concave. In this setup, irrigation efficiency is expected to impact farm revenue only indirectly, by transforming applied water into effective water. It would also be possible to consider a direct impact of irrigation efficiency on farm revenue, if it allowed farmers better to fulfill crop water requirements during critical growth (Pfeiffer and Lin, 2014a). Note that we do not model crop adjustments explicitly, although these contribute to the properties of the revenue function.

The marginal cost of groundwater extraction at time t is given by $C(\varepsilon, G_t)$, thus, we allow it to depend on irrigation efficiency as well as on the stock of groundwater at time t, G_t. As more energy has to be spent to pump the same unit of water from the aquifer the lower the stock of groundwater, the marginal cost of pumping increases the more depleted the stock, that is, $\frac{\partial C(\varepsilon, G_t)}{\partial G_t} < 0$, though at a decreasing rate $\frac{\partial^2 C(\varepsilon, G_t)}{\partial G_t^2} > 0$. Finally, in what concerns the impact of more efficient technologies on the marginal cost of extraction there is no consensus in the literature. In line with Gómez and Pérez-Blanco (2014), we assume that $\frac{\partial C(\varepsilon, G_t)}{\partial \varepsilon} > 0$, as the cost of energy may increase for more efficient irrigation systems, which tend to be more sophisticated.[5] Nonetheless, we also explore the case in which the marginal cost of pumping does not depend on efficiency, that is, $\frac{\partial C(\varepsilon, G_t)}{\partial \varepsilon} = 0$.

The representative farm's decision problem consists of maximizing current profits at every time t by deciding the amount of water to be withdrawn and applied for a given technical irrigation efficiency, ε, and a given stock of groundwater, G_t, as follows:

$$\underset{x_t}{Max}\, \Pi_t = y_t(\varepsilon x_t; \theta) - C(\varepsilon, G_t)x_t \tag{1}$$

The first-order condition for an interior solution can be stated as follows:

$$\frac{\partial y(\varepsilon x_t; \theta)}{\partial(\varepsilon x_t)}\varepsilon - C(\varepsilon, G_t) = 0 \tag{2}$$

yielding

$$\frac{\partial y(\varepsilon_t x_t; \theta)}{\partial(\varepsilon_t x_t)} = \frac{C(\varepsilon_t, G_t)}{\varepsilon_t}. \tag{3}$$

From (3), we conclude that the farmer maximizes current profits by deciding to pump the amount of water for which marginal benefit equals marginal cost, that is, when marginal net benefit is zero at each time period, *ceteris paribus.*

In order to understand better the impact of an increase in irrigation efficiency on applied water, we differentiate totally (3) with respect to x_t, ε_t and G_t, obtaining $\frac{\partial^2 y_t(.)}{\partial(\varepsilon_t x_t)^2}\varepsilon^2 dx_t = \frac{\partial C(\varepsilon_t, G_t)}{\partial G_t}dG_t + \left[\frac{\partial C(\varepsilon_t, G_t)}{\partial \varepsilon_t} - \frac{\partial^2 y_t(.)}{\partial(\varepsilon_t x_t)^2}x_t\varepsilon_t - \frac{\partial\ y_t(.)}{\partial(\varepsilon_t x_t)}\right]d\varepsilon_t$. From here we see that an increase in the stock of groundwater increases the amount of applied

[5] This assumption may not hold in all cases. See Pfeiffer and Lin (2014a).

water, $\frac{dx_t}{dG_t} > 0$, since the farmer's marginal cost of pumping decreases. In contrast, a change in irrigation efficiency has an ambiguous effect on the amount of applied water. In particular, even if the change in irrigation efficiency does not affect the marginal cost of pumping, $\frac{\partial C(\varepsilon_t, G_t)}{\partial \varepsilon_t} = 0$, the result depends on how large the second-order effects in the marginal revenue compared with the first-order ones. To understand the ambiguity, it is instructive to consider the decision in terms of effective water, g_t. An improvement in efficiency does not change the marginal benefit of one extra unit of effective water, but it does unambiguously lower its marginal cost, $\partial \frac{\left(\frac{C(\varepsilon_t, G_t)}{\varepsilon_t}\right)}{\partial \varepsilon_t} < 0$.[6] Therefore, in this case, optimal effective water will increase with efficiency. However, fewer units of applied water are now necessary per unit of effective water, so the final effect on x_t cannot be signed in general.

Finally, from (2), and given that the farmer's revenue is monotonic, it is possible to implicitly derive the demand function for effective water, g_t, that is:

$$g_t = \varepsilon_t x_t = D\left(\frac{C(\varepsilon_t, G_t)}{\varepsilon_t}\right) \tag{4}$$

where $C(\varepsilon_t, G_t)$ represents the marginal cost of pumping. From (4), we may obtain the demand function for applied water, x_t [7]

[6] Note that from (3) expressed in terms of g_t, $\frac{\partial\left(\frac{C(\varepsilon_t, G_t)}{\varepsilon_t}\right)}{\partial \varepsilon_t} = \frac{1}{\varepsilon_t}\left[\frac{\partial C(\varepsilon_t, G_t)}{\partial \varepsilon_t} - \frac{C(\varepsilon_t, G_t)}{\varepsilon_t}\right]$.

[7] Based on (5) we may derive the elasticity of demand of g with respect to efficiency (see Pfeiffer and Lin, 2014a, and Gomez and Pérez-Blanco, 2014).

$$x_t = \frac{D\left(\frac{C(\varepsilon, G_t)}{\varepsilon}\right)}{\varepsilon} \tag{5}$$

Social Planner Solution

Assuming that the aquifer is managed optimally, the problem facing a social planner consists of choosing the optimal path for the consumptive use of water for each farmer by maximizing the total present value of net revenues at each time period using a constant discount rate r.[8] Therefore, the intertemporal optimization social planner's problem can be stated as follows:

$$\underset{\{x_t\}}{Max} V(G_t; \varepsilon_t, \theta) = \int_0^{\infty} \left[ny(\varepsilon x_t; \theta) - nC(\varepsilon_t, G_t)x_t\right] e^{-rt} dt \tag{6}$$

s. to

$$\dot{G} = R + nx_t\left[\alpha(\varepsilon) - 1\right] \tag{7}$$

$$G_0 = \overline{G}$$
$$G_t \geq 0$$

where R represents the constant recharge of the aquifer, and $0 < \alpha(\varepsilon) < 1$ stands for the recharge of the aquifer via percolation, which depends negatively on irrigation efficiency, $\frac{\partial \alpha(\varepsilon)}{\partial \varepsilon} < 0$, since improved efficiency typically means less water returning to the aquifer from the field, *ceteris paribus*.[9] Finally, $G_0 = \overline{G}$ is the initial condition for the stock.

The current value Hamiltonian can be stated as follows:

$$H = ny(\varepsilon x_t; \theta) - nC(\varepsilon, G_t)x_t + \lambda_t (R + nx_t\left[\alpha(\varepsilon) - 1\right]) \tag{8}$$

[8] No environmental externalities are considered.

[9] See, for instance, Quintana, Ashwell and Peterson (2016) and Scheierling et al. (2016).

The first-order conditions for an interior solution of (6) are given by:

$$\frac{\partial y_t(.)}{\partial(\varepsilon x_t)}\varepsilon = C(\varepsilon, G_t) + (1-\alpha(\varepsilon))\lambda_t \tag{9}$$

$$\dot{\lambda} = r\lambda_t + n\frac{\partial C(\varepsilon, G_t)}{\partial G_t}x_t \tag{10}$$

Therefore, at the steady-state, that is, for $\dot{\lambda} = 0$ and $\dot{G} = 0$, we obtain that

$$\lambda^s = \frac{-n\dfrac{\partial C(\varepsilon, G_t)}{\partial G_t}x_t}{r} \tag{11}$$

$$\dot{G} = 0 \Leftrightarrow x^s = \frac{R}{n[1-\alpha(\varepsilon)]} \tag{12}$$

Equation (12) helps in the comparison between the optimal and the myopic cases, because it holds whenever a steady state exists. Thus x^s always takes the same value for given values of the parameters. Comparing (2) with (9) we may therefore conclude, as expected, that the steady state stock is lower when firms behave myopically.

Using the implicit function theorem to solve (9), we may obtain $\frac{\partial \hat{x}}{\partial G}$ and $\frac{\partial \hat{x}}{\partial \lambda}$ by totally differentiating (9) with respect to G_t, and λ_t, where x is a locally differentiable function of G, and λ, that is, $x = \hat{x}(\lambda, G)$. Hence, we have that:

$$\begin{aligned}\frac{\partial^2 y_t(.)}{\partial(\varepsilon_t x_t)^2}\varepsilon^2 dx_t &= \frac{\partial C(\varepsilon_t, G_t)}{\partial G_t}dG_t + (1-\alpha(\varepsilon_t))d\lambda_t + \\ &+\left[\frac{\partial C(\varepsilon_t, G_t)}{\partial \varepsilon_t} - \frac{\partial \alpha(\varepsilon_t)}{\partial \varepsilon_t}\lambda_t - \frac{\partial^2 y_t(.)}{\partial(\varepsilon_t x_t)^2}x_t\varepsilon_t - \frac{\partial y_t(.)}{\partial(\varepsilon x_t)}\right]d\varepsilon_t\end{aligned} \tag{13}$$

Assuming again that an increase in irrigation efficiency increases the marginal cost of pumping, that is, $\frac{\partial C(\varepsilon_t, G_t)}{\partial \varepsilon_t} > 0$, we conclude that

$$\frac{\partial \hat{x}}{\partial G} = \frac{\frac{\partial C(\varepsilon, G_t)}{\partial G}}{\frac{\partial^2 y_t(.)}{\partial(\varepsilon x_t)^2}\varepsilon^2} > 0, \tag{14}$$

$$\frac{\partial \hat{x}}{\partial \lambda} = \frac{(1-\alpha(\varepsilon))}{\frac{\partial^2 y_t(.)}{\partial(\varepsilon x_t)^2}\varepsilon^2} < 0, \tag{15}$$

and

$$\frac{\partial \hat{x}}{\partial \varepsilon} = \frac{\frac{\partial C(\varepsilon, G_t)}{\partial \varepsilon} - \frac{\partial y_t(.)}{\partial(\varepsilon x_t)} - \frac{\partial \alpha(\varepsilon)}{\partial \varepsilon}\lambda - \frac{\partial^2 y_t(.)}{\partial(\varepsilon x_t)^2}x\varepsilon}{\frac{\partial^2 y_t(.)}{\partial(\varepsilon x_t)^2}\varepsilon^2}, \tag{16}$$

Since $\frac{\partial^2 y_t(.)}{\partial(\varepsilon x_t)^2} < 0$, $\frac{\partial \alpha(\varepsilon)}{\partial \varepsilon} < 0$, and $\frac{\partial y_t(.)}{\partial(\varepsilon x_t)} > 0$, the sign of (16) is ambiguous, as the first two terms in the numerator are negative, while the last two are positive. Note that, as in the myopic case, if $\frac{\partial C(\varepsilon, G_t)}{\partial \varepsilon} = 0$ the sign of (16) is still ambiguous.

The next step is to eliminate x from (7) and (10) using $x = \hat{x}(\lambda, G)$, yielding

$$\dot{\lambda} = r\lambda_t + n\frac{\partial C(\varepsilon_t, G_t)}{\partial G_t}\hat{x}(\lambda, G) \tag{17}$$

$$\dot{G} = R + n\hat{x}(\lambda, G)\left[\alpha(\varepsilon_t) - 1\right] \tag{18}$$

The steady-state solution $(\lambda^s(\varepsilon,..), G^s(\varepsilon,..))$ of the necessary and sufficient conditions (17) and (18) can be obtained by setting $\dot{G} = 0$ and $\dot{\lambda} = 0$

$$r\lambda + n\frac{\partial C(.)}{\partial G}\hat{x}(\lambda, G) \equiv 0$$
$$R + n\hat{x}(\lambda, G)\left[\alpha(\varepsilon) - 1\right] \equiv 0 \qquad (19)$$

and solving simultaneously for λ and G in terms of the parameters of the model.

To determine the local stability of the fixed point $(\lambda^s(\varepsilon,..), G^s(\varepsilon,..))$ we calculate the Jacobian matrix of the dynamic system (17) and (18) with respect to λ and G, and evaluate it at $(\lambda^s(\varepsilon,..), G^s(\varepsilon,..))$, obtaining

$$|J| = \begin{vmatrix} \frac{\partial \dot{\lambda}}{\partial \lambda} & \frac{\partial \dot{\lambda}}{\partial G} \\ \frac{\partial \dot{G}}{\partial \lambda} & \frac{\partial \dot{G}}{\partial G} \end{vmatrix}_{\substack{\dot{\lambda}=0 \\ \dot{G}=0}} = \begin{vmatrix} r + n\frac{\partial C}{\partial G}\frac{\partial \hat{x}}{\partial \lambda} & n\frac{\partial^2 C}{\partial G^2}\hat{x} + n\frac{\partial C}{\partial G}\frac{\partial \hat{x}}{\partial G} \\ n\frac{\partial \hat{x}}{\partial \lambda}(\alpha(\varepsilon) - 1) & n\frac{\partial \hat{x}}{\partial G}(\alpha(\varepsilon) - 1) \end{vmatrix} \qquad (20)$$

In what concerns the sign of $|J|$: if the sign of $\left(n\frac{\partial^2 C}{\partial G^2}\hat{x} + n\frac{\partial C}{\partial G}\frac{\partial \hat{x}}{\partial G}\right)$ is positive, where the first term is positive and the second is negative, according to the previously stated assumptions, the determinant of the Jacobian matrix is negative. By inspection, we may conclude that this expression is positive when the second-order effects of depletion on the marginal cost of pumping dominate the first-order effects, and it is negative otherwise. Therefore, the sign of this term is conditional on the state of the groundwater stock and it is expected to be positive for more depleted stocks, which can be considered the more relevant case. In this case, $|J|$ is negative and the steady state is locally stable.[10]

[10] In other words, $\left(n\frac{\partial^2 C(.)}{\partial G^2} + n\frac{\partial C(.)}{\partial G}\frac{\partial \hat{x}}{\partial G}\right) > 0$ is a sufficient condition for $|J| < 0$. In this case, the local stability of the steady-state $(\lambda^s(\varepsilon,..), G^s(\varepsilon,..))$ of the nonlinear system of equations (17) and (18) is an unstable saddle point, with two trajectories in the (λ, G) phase plane converging to it as $t \to \infty$, allowing a comparative statics analysis of the steady state (Caputo, 2005).

In order to derive the steady state comparative statics of a change in the irrigation efficiency technology, ε, we may state in identity form the necessary and sufficient conditions (19) as follows:

$$\begin{aligned} & r\,\lambda^{s}(\varepsilon,..)+n\frac{\partial C(\varepsilon,G^{s}(\varepsilon,..))}{\partial G}\hat{x}(\lambda^{s}(\varepsilon,..),G^{s}(\varepsilon,..))\equiv 0 \\ & R+n\hat{x}(\lambda^{s}(\varepsilon,..),G^{s}(\varepsilon,..))\left[\alpha(\varepsilon)-1\right]\equiv 0 \end{aligned} \tag{21}$$

By differentiating (21) with respect to ε, we obtain:

$$\begin{aligned} & r\frac{\partial\lambda^{s}(\varepsilon,..)}{\partial\varepsilon}+n\frac{\partial^{2}C(.)}{\partial G^{2}}\frac{\partial G^{s}}{\partial\varepsilon}\hat{x}+n\frac{\partial^{2}C(.)}{\partial G\partial\varepsilon}\hat{x}+n\frac{\partial C(.)}{\partial G}\left[\frac{\partial\hat{x}}{\partial\lambda}\frac{\partial\lambda^{s}(.)}{\partial\varepsilon}+\frac{\partial\hat{x}}{\partial G}\frac{\partial G^{s}(.)}{\partial\varepsilon}\right]\equiv 0 \\ & n\left[\frac{\partial\hat{x}}{\partial\lambda}\frac{\partial\lambda^{s}(.)}{\partial\varepsilon}+\frac{\partial\hat{x}}{\partial G}\frac{\partial G^{s}(.)}{\partial\varepsilon}\right]\left[\alpha(\varepsilon)-1\right]+n\hat{x}\left(\frac{\partial\alpha(\varepsilon)}{\partial\varepsilon}\right)\equiv 0 \end{aligned} \tag{22}$$

Using Cramer's rule we obtain:

$$\frac{\partial\lambda^{s}}{\partial\varepsilon}=\frac{\left(-n\frac{\partial^{2}C(.)}{\partial G\partial\varepsilon}\hat{x}\right)\left(n\frac{\partial\hat{x}}{\partial G}\left[\alpha(\varepsilon)-1\right]\right)}{|J|}+ \\ +\frac{\left(n\frac{\partial^{2}C(.)}{\partial G^{2}}\hat{x}+n\frac{\partial C(.)}{\partial G}\frac{\partial\hat{x}}{\partial G}\right)\left(n\hat{x}\frac{\partial\alpha}{\partial\varepsilon}\right)}{|J|} \tag{23}$$

$$\frac{\partial G^{s}}{\partial\varepsilon}=\frac{\left[r+n\frac{\partial C(.)}{\partial G}\frac{\partial\hat{x}}{\partial\lambda}\right]\left(-n\hat{x}\frac{\partial\alpha}{\partial\varepsilon}\right)+\left(n\frac{\partial^{2}C(.)}{\partial G\partial\varepsilon}\hat{x}\right)n\frac{\partial\hat{x}}{\partial\lambda}\left[\alpha(\varepsilon)-1\right]}{|J|} \tag{24}$$

As $|J|<0$, the denominators of (23) and (24) are negative. Yet, while the sign of the numerator of (23) is ambiguous, the one of (24) is positive, implying that $\frac{\partial G^{s}}{\partial\varepsilon}<0$. Therefore, we conclude that an increase in irrigation efficiency decreases the steady-stock of groundwater. In this sense, we can state that the increase in irrigation efficiency backfires in terms of stock size, even if the impact on steady state applied water x^s is negative since, from (12), we know that

$$\frac{\partial x^s}{\partial \varepsilon} = \frac{x^s \frac{\partial \alpha}{\partial \varepsilon}}{(1-\alpha(\varepsilon))} < 0 . \tag{25}$$

Therefore, in a dynamic context the analysis of the stock size is of great relevance. Interestingly enough, if $\frac{\partial^2 C(.)}{\partial G \partial \varepsilon} = 0$, the signs of both (23) and (24) are well defined, with $\frac{\partial \lambda^s}{\partial \varepsilon} > 0$, and $\frac{\partial G^s}{\partial \varepsilon} < 0$, so that an increase in irrigation efficiency still affects the stock negatively, but now also unambiguously increases the value of the resource.[11]

Finally, whether or not rebound exists in terms of effective water, g^s, can be assessed through the efficiency elasticity of effective water, that is,

$$\eta_{\varepsilon,g} = \frac{\partial g^s}{\partial \varepsilon}\frac{\varepsilon}{g^s} = \frac{1}{x^s}\left[x^s + \varepsilon\frac{\partial x^s}{\partial \varepsilon}\right] = 1 + \eta_{\varepsilon,x} = 1 - \frac{\varepsilon \frac{\partial \alpha}{\partial \varepsilon}}{(1-\alpha(\varepsilon))} . \tag{26}$$

using (25). Therefore, from (26), the sign of $\eta_{\varepsilon,g}$ depends on whether the ratio $\frac{\frac{\partial \alpha}{\partial \varepsilon}}{(1-\alpha(\varepsilon))}$ is smaller or higher than one. Since $\varepsilon \in [0,1]$, if that ratio is smaller than one the elasticity is positive and lower than one. That is, an increase in irrigation efficiency increases the amount of effective water less than proportionally, as the impact on applied water prevails. Yet, if that ratio is higher than one, the result is ambiguous. Note that for the same irrigation efficiency the fraction of

[11] Note that in the case $\frac{\partial^2 C(.)}{\partial G \partial \varepsilon} < 0$ the sign of (24) is ambiguous. Nonetheless, backfiring may still occur.

applied water that returns (runoff), $\alpha(\varepsilon)$, is affected by the climatic conditions.[12] In the driest irrigated regions of southern Europe where rain is scarce and the number of hours of sunlight exposure is very high, $\alpha(\varepsilon)$ is expected to be very low implying that the ratio is also small, *ceteris paribus*. In this case, though negative, (26) is likely to be close to zero, or may become positive. Ultimately, this is an empirical issue.

In this setup, it is clear that water and energy prices may play an important role in promoting sustainable use of the resource for policy purposes. From (2) and (10), for the same stock of water in the aquifer and the same irrigation efficiency technology, the social marginal cost of pumping is higher than the private marginal cost implying that if the intertemporal externality of pumping from the aquifer is taken into account farmers should pay a higher price per cubic meter of water. Moreover, in the presence of more efficient irrigation technologies, potential water savings may increase consumption (rebound effect) or decrease groundwater stock. In this case, the demand for energy may increase, increasing energy prices and restoring the incentive to preserve the resource. Zilberman et al. (2008) developed theoretical models to study the effects of rising energy prices on the economics of water in agriculture, and found that higher energy costs increase significantly the cost of groundwater. In this line of research, Pfeiffer and Lin (2014b) show that higher energy prices decrease water use along both the intensive and extensive margins. Based on these results, the authors suggest that policies that reduce

[12] As Grafton et al. (2018) point out, irrigation efficiency improvements at farm scale do not typically increase the water availability at a watershed and basin scale, as many of the previously non-consumed water "losses" at a farm scale (for example, runoff) are recovered and reused elsewhere. Thus, the hydrological properties of the watershed are crucial to understand the relationship between irrigation efficiency and water extraction. More generally, the authors suggest a reform of the current policy agenda in a way that focuses on watershed-level water accounts and considers actual irrigation behavior, among other aspects.

energy prices would cause groundwater extraction to increase, therefore raising a potential concern about declining water table levels in many productive agricultural basins worldwide that depend on groundwater. This issue will be further explored in the next section.

A final remark is in order. As the results are location-specific, they are often unclear from a theoretical perspective suggesting that more empirical investigation is needed. Hence, other examples can be considered that may also originate different limit cases. One of them is related to the use of renewable energy sources to pump water from the ground, and is discussed in the next section.

3. Using Renewable Energy Sources for Pumping

Worldwide climate change mitigation and adaptation have been at the center of the political agenda related to the transition to a low carbon future. In this context, worldwide renewable energy sources have been granted significant amounts of resources to incentivize technological innovation and encourage early deployment. Portugal was no exception, as one of the EU member countries where the share of electricity from renewable sources in the energy mix is largest. The link between renewable energy deployment and the use of other resources, however, is seldom assessed.

In this section, we consider the case of a representative farmer who produces in a dry region which in recent years has been experiencing droughts. We assume that the energy that is used for pumping the water from the aquifer is generated from renewable energy sources (such as solar panels). In order to reduce the impact of the lack of water the government decides to subsidize the drilling water holes. So, we assume that the farmer has to pay a fixed cost, F , which is subsidized, to drill the hole.[13] As in Section 2 we consider first the myopic solution and we compare it with the social planner's.

Myopic Decision Problem

In this case, the representative farmer's problem can be stated as follows:

$$\underset{x_t}{Max}\, \Pi_t = y_t(\varepsilon x_t;\theta) - F \tag{27}$$

As long as profit is non-negative the investment is worthwhile. Therefore, in this case, as the farmer faces decreasing average costs it is optimal to pump as much as possible, which, in some cases, may lead to total depletion.[14] From the first-order condition each farmer maximizes profits at t when marginal revenue is zero. Given strict concavity of the revenue function this implies that it is optimal to pump as much as possible. Myopia in this case can have very negative consequences for groundwater, eventually leading to depletion of the stock.[15]

Social Planner's Problem

In this case, the problem can be stated as follows:

$$\underset{\{x_t\}}{Max}\, V(G_t;\varepsilon_t,\theta) = -nF + \int_0^{\infty}\left[ny(\varepsilon x_t;\theta)\right]e^{-rt}\,dt \tag{28}$$

s. to

$$\dot{G} = R + nx_t\left[\alpha(\varepsilon) - 1\right] \tag{29}$$

[13] In this case we assume that the subsidy is granted for a specific technology. In alternative, it could be the case that the landowner can choose the type of technology, and, therefore, the drilling capacity per hour.
[14] Note that in this case if the fixed cost is fully subsidized we could even not include it in the decision problem.
[15] Though, if the climatic conditions allow, it is likely that some water will return to the aquifer.

$$G_0 = \overline{G}$$
$$G_t \geq 0 \tag{30}$$

where we assume that it is worth investing in the infrastructure, that is,

$$\int_0^{\infty} \left[ny(\varepsilon x_t;\theta) \right] e^{-rt} dt > Fn . \tag{31}$$

The current value Hamiltonian can be stated as follows:

$$H = ny(\varepsilon_t x_t;\theta) + \lambda_t (R + nx_t \left[\alpha(\varepsilon_t) - 1 \right]) \tag{32}$$

The first-order conditions for an interior solution are given by:

$$\frac{\partial y_t(.)}{\partial(\varepsilon x_t)} \varepsilon_t = (1 - \alpha(\varepsilon_t))\lambda_t \tag{33}$$

$$\dot{\lambda} = r\lambda_t \tag{34}$$

Note that, in contrast to the social planner's decision problem discussed in the previous section, as the condition of the stock in the aquifer does not impact the marginal cost of extraction anymore (marginal user cost is zero), the intertemporal externality via stock effect is eliminated in this new setup. Its consequences are investigated below.

By differentiating (33) with respect to time, substituting in (34) and simplifying, we obtain:

$$\frac{\dot{x}}{x} = -\frac{1}{\varepsilon_t} \frac{r}{\left| \eta_{MR_g, x_t} \right|} \tag{35}$$

where $g_t = \varepsilon_t x_t$, and the denominator of the above expression represents the elasticity of the marginal revenue of the applied water in absolute value. Therefore, its growth rate, $\frac{\dot{x}}{x}$, is negative, as long as $r > 0$, implying that applied water will decrease over time.

This solution is not viable, as crop needs will not be met. Moreover, it also implies that costs are increasing. From (34), we obtain Hotelling's rule, according to which the shadow price of the resource shall increase over time at the discount rate, while consumption decreases to zero, implying depletion of the entire stock.[16] Therefore, this result is not sustainable, as optimality requires a balance between preservation and use.

In contrast, if $r = 0$, pumping $x^s = \frac{R}{n[1-\alpha(\varepsilon_t)]}$ at each time period, for which $\dot{G} = 0$, applied water is kept constant over time.

Therefore, and in contrast to Section 2, if the new pumping technology eliminates the possibility of internalizing the stock effect via the marginal cost of pumping, neither the price of the resource signals scarcity nor energy prices can be used to incentivize preservation in the context of our model, implying that the incentive to preserve the resource via those prices is lost. As mentioned before, Pfeiffer and Lin (2014b) point out the negative consequences that policies that reduce energy prices would cause on water table levels in many productive agricultural basins worldwide that depend on groundwater. Therefore, the use of renewable energy sources for pumping water from aquifers is an example of a policy with extreme consequences. In order to restore the incentive to preserve, the alternative that is left to the social planner is to intervene by regulating the amount of water that can be pumped from the aquifer. As mentioned by Pérez-Blanco et al. (2018) the success of Water Conservation Technologies (WCTs) require "Water Conservation Policies (WCPs) that strengthen irrigators' water constraints".

4. Discussion

[16] This result is similar to the "cake-eating" problem in the basic depletable resource problem. See Heal (1993).

In this paper we use an intertemporal model of groundwater extraction for irrigation purposes to explore the consequences of increasing technical efficiency in water use. We then consider the use of renewable sources to pump the water from the ground.

The motivation for this paper is related to the discussion surrounding the enlargement of the irrigated areas in southern Portugal, and the incentive policy that has been followed. This region is the driest in the country, and, according to climate change scenarios, the situation is expected to worsen in the future, with higher temperatures and decreasing precipitation levels. Therefore, in the presence of a positive scarcity cost of water, a sustainable use of water supply is required, which implies an appropriate design of water price instruments.

Energy conservation policies may aggravate the problem of water scarcity. For instance, energy-efficiency improvements for irrigation systems without taking into account the physical constraint on the total amount of water available, such as in the case of pumping from aquifers, that is, without considering the scarcity cost of water, can lead to unsustainable solutions. Therefore, instruments should be designed in order to integrate incentives for energy conservation and limitation of rebound and backfire effects.

The consequences of ignoring the scarcity cost of water are even more serious when renewable sources are used to pump the water from the ground. As in the example we have considered, subsidizing water drilling combined with the use of renewable energy sources for pumping provides perverse incentives to the economic agents. Therefore, no incentives to conserve water are provided, contributing to an increase in the rebound effect.

Moreover, in many aquifers there are significant environmental links with watershed ecosystems. Such environmental effects ought to be considered in welfare assessment, as pointed out in Esteban and Albiac (2011) and Pereau and Pryet (2018), where damage functions are assumed to be dependent on groundwater stock. Alternative water uses, such as industrial, urban or recreational, will have different impacts, which must also be taken into account if sustainable water use is to be achieved. This is even more important under climate change conditions, where the buffer value of groundwater in times of drought is heightened.

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