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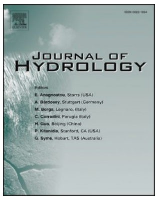

Research papers

Hydro-economic basin impacts of extensive adoption of deficit irrigation by farmers: Are we overestimating water resources?

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ABSTRACT

Deficit irrigation (DI) is an agronomic practice in which the volume of irrigation water applied is below maximum yield requirements, usually during drought-sensitive growth stages. DI is often used when water is scarce, and farmers need to either reduce the irrigated area or reduce the water supply to the existing irrigated area. This research presents an agroeconomic model of field efficiencies and related losses to study the relationship between DI adoption and return flows (RF). Results show that RF are significantly overestimated when DI is widely adopted as there are no losses when relative irrigation supply (ν) is low. The hydrological impact at basin level has been illustrated for the Guadalquivir River Basin, showing that RF and water resources are substantially overestimated when constant efficiency values (an assumption common to many hydrological models) are used without including the impact of DI on RF.

1. Introduction

Pressures on productive land and water resources are driving the productive capacity of agricultural ecosystems, with global land use dedicated to food production increasing by 15 % between 1961 and 2019. However, breaking down this increase, irrigated cropping increased by 110 %, while rainfed cropping increased by only 2.6 % (FAO, 2022). The demand for water consumption worldwide has grown by 800 % over the last century, while the world's population is projected to reach 9.8 billion in 2050 (United Nations, 2018). Berbel et al. (2020) predict a scenario for 2050 in which water withdrawal has increased by around 60 % relative to 2010. Globally, there is a consensus that meeting food and economic needs will put greater stress on water resources, especially irrigation water, which accounts for around 70 % of water withdrawal worldwide. As such, there is a need to increase the beneficial output (e.g., crop yield) to the amount of water used in the process known as water productivity per unit of irrigation supplied (WP_{SI}) and the use of DI as an agronomic practice.

The more traditional economic analysis of water use is focused on the scenario where land is the limiting factor and optimal water supply is determined as the maximum return to land, with the associated optimum water use. This is the decision-making context in regions where the water saved cannot be used in additional new irrigated land. This limit on land may be determined by technical and natural characteristics (limited suitable land either agronomically or economically) or by institutional ones (e.g., in Spain, the water rights simultaneously limit the irrigated area and the volume used).

The economic optimization of water use when land is limited (traditional paradigm) has been studied elsewhere and the general conclusion is that the economic optimum is not under maximum yield but very close to it. Most of the analysis have been done in a context of static optimization and certainty, and based on a water production function that is linear (Steduto et al., 2012), although some perennial crops such as olive (Vita Serman et al., 2021) and almond have a quadratic response (Goldhamer and Fereres, 2017). Berbel et al. (2018) conducted a detailed analysis of the elasticity of demand under different system efficiency values for this context, while Berbel and Expósito (2022) presented an analysis of the economic optimum of irrigation water under uncertainty.

When the limiting factor is land and there are abundant water re-

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sources, it implies that the available water is not fully consumed in normal circumstances, as decision-making is aimed at maximizing the return to land, and in this decision-making context water supply is not a limiting factor. This context changes in a drought scenario when water supply is reduced temporarily. If there is a significant share of arable crops, farmers have some freedom to reallocate resources, meaning that they can allocate the scarce water as the limiting factor to maximise return to water. A different context appears when perennial trees dominate the crop plan, so that farmer strategies during drought conditions are aimed at ensuring the survival of the trees and preventing irreversible damage to the biological capital (Moldero et al., 2021). A detailed analysis of farmers' response when land is limited and water is unlimited has been conducted by Berbel and Mateos (2014) and Berbel et al. (2018), that present a thorough examination of the impact of irrigation efficiency (*E*) on water demand; readers may refer to these publications for a more in-depth study of the land limited context.

This paper focuses on a context that has been somewhat underexplored; when water is scarce relative to land, or in an extreme case, land is unlimited, and water supply is limited. This context, where most of the crops cannot be fully irrigated, may be structural (water scarcity as consequence of unsustainable irrigation expansion) or temporal (drought conditions).

Due to the scarce literature available on these effects at river basin level, and the need for their measurement to assist in the design of effective water management policies, this work aims to analyse hydrological and economic consequences of widespread adoption of DI in a basin where water is the limiting factor, and to address the gap between river basin planning and hydro-economic models in simulated RF.

Besides the agronomic and economic analysis of DI impacts, there is a need to explore the impacts relating to the hydro-economic models that are used to support water policy decisions. For this purpose, this introduction includes a state of the art on DI, and a review of how RF have been addressed in the most cited hydro economic models in arid and semi-arid areas.

The main contributions of this paper are the following: First, a quantitative estimation of effect of DI on RF has been done at basin scale with comparison to the river basin management plan assumptions; Second, an available model that relates DI with crop prices, agronomic Y-ET response (Ky), fixed cultivation cost (FC) and crop sale price (Py) is applied to a large Mediterranean basin (Guadalquivir, southern Spain), finding the 'DI solution' for the main crops and testing this 'DI solution' with overall farmers behaviour; Third, a quantitative estimation of "DI altered RF" is done and the results are compared to the current River Basin Management Plan.

It is important to highlight that *E* is defined throughout this study as the irrigation water that is stored in the soil, (more accurately in the root zone, accessible for the crop and ready to be evapotranspired), divided by the applied irrigation water.

2. Novel Insights into the Implementation of Deficit Irrigation

DI is an agronomic strategy in which the amount of water applied is below crop evapotranspiration requirements for maximum yield (ET_m). In other words, irrigation supply under DI is less than that needed to meet maximum ET (English, 1990). Regulated deficit irrigation (RDI) is a strategy in which available water for irrigation is applied selectively during drought-sensitive growth stages of a crop. Fereres and Soriano (2007) reviewed the use of RDI in arable and perennial crops, reporting that RDI practices are multifaceted, and lead to changes at the technical, socio-economic, and institutional levels. Precise application of RDI requires the right infrastructure to regulate and manage water supply with flexibility, precision, and certainty. In turn, governance institutions are needed to ensure the application of the required characteristics in distribution systems and the water supply.

There is growing interest in DI as a strategy that enables adaption to water scarcity and consequently increases WP_{SI}. Fig. 1 shows the evolution in the number of articles in the Web of Science database that address the topic 'deficit irrigation'.

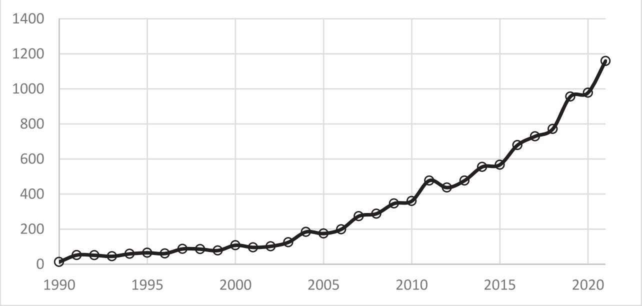

Fig. 1. Number of articles per year under the topic 'deficit irrigation' in the Web of Science database (searched in December 2022).

Most of the published articles are focused on the management strategies and the consequences for water productivity. Some articles also report that in many horticultural crops, moderate RDI increases farmer profits (Fereres and Soriano, 2007). DI can be applied to horticultural, arable, or perennial crops, and applied research has analysed optimal strategies for specific crops (Chaves et al., 2007; Costa et al., 2007; Deluc et al., 2009; Himanshu et al., 2023; Moriana et al., 2003; Patanè et al., 2011).

On the other hand, there has been relatively little analysis of the global economic and hydrological impact of the widespread adoption of DI strategies. Expósito and Berbel (2019) described the process of basin closure in the Guadalquivir River Basin (Southern Spain), explaining the role of DI practices (mainly in olive groves) to increase water productivity. Tocados-Franco et al. (2022) analysed the evolution of water supply and demand in the Guadalquivir Basin, showing that the ratio of water supply to irrigation needs in the basin was around 0.50 by the year 2020, and illustrating the predominance of DI in the basin.

There are several key findings from the recent literature on the relationship between DI adoption, scarcity and irrigation modernization.

First, DI is an agronomic practice that is likely to be widely adopted as a structural response to: a) growing scarcity due to greater demands from economic uses (farming, industry, the general public, increasing food needs); b) climate change, (certainty regarding rising temperatures and ET, uncertainty about decreasing precipitation); and c) increasing environmental and societal demands for water use sustainability (implying a need to reduce irrigation volumes) (see Rai et al. (2022) for a recent review on this issue).

Second, DI is a practice that is facilitated by modernization and better knowledge of agronomic practices (sensitivity stages, techniques, digitalization), as Touil et al. (2022) conclude in their review.

Third, the spread of DI is supported by the increase in water productivity (Kg/m^3 and \$/m^3); see Yang et al. (2022) for a recent review of the impact of DI on water productivity.

Fourth, there is evidence of irrigation technology having an impact on situations of water scarcity, improving ν and water productivity. A recent review by Benavides et al. (2021) of 264 irrigation schemes (in 25 countries) found that on-demand delivery showed a mean ν below one (0.95), while irrigation schemes with pipe distribution systems gave the lowest mean ν (0.79), dropping to a mean value of 0.62 for combinations of localized and sprinkler systems. All the values listed below the unit exemplify scenarios where DI is broadly applied. In contrast, distribution networks that solely utilize open channels displayed an average ν of 2.59, making the implementation of DI improbable in such situations.

Fifth, the use of hydro-economic models for water accounting and water management will become more common in the future, and they will be incorporated as an essential planning tool (Expósito et al., 2020). Therefore, a proper estimation of RF is critical for an approximate register of the water resources in the catchment area. A recent review (Bassi et al., 2020) of water accounting models in India found that irrigation RF are missing or oversimplified in most of the models. According to the authors, none of the available models properly calculate RF from irrigation (and other uses).

3. The treatment of return flows in hydro-economic models

Hydro-economic models are complex, and if they are to be useful for policy making, they need to consider many interacting variables and parameters at the same time. The literature on hydro-economic modelling covers a wide range of topics, locations and trends related to water resources. Harou et al. (2009) and Ward (2021) have conducted extensive reviews showing that the hydro-economic approach is appropriate for promoting the integration of engineering, economics, and hydrology in the development of water resources management strategies. However, for these tools to be effective, the estimates and underlying assumptions they rely on must be correct (Eluwa et al., 2023). The state of each variable/parameter determines the outcomes of others: for example, an overestimation of RF distorts the water balance.

Efforts to improve the use of scarce water resources centre on the implementation of water-saving methods such as improving *E*, alternative cropping systems or DI, among others. Hence, it is important to analyse in detail how these RF are being dealt with in the hydro-economic models used to address the challenges related to the management and implementation of water management policies.

Table 1 shows a review of the most influential hydro-economic models developed in the last decade in arid or semi-arid areas of the world. RF (in parts per unit) are generally treated as the remainder of the *E* respect to the unit ($1 - E_0 = RF$). The standard *E* coefficient used in hydrological planning (E_0) is considered normally a fixed coefficient for each irrigation system, and it is assumed about 95 % for drip irrigation systems, 80 % for sprinkler irrigation systems and 60 % for furrow irrigation systems. In Table 1, only Maneta et al. (2020) and Kahil et al. (2018) adopt a fixed E_0 coefficient for all crops and irrigation systems. Other hydro-economic models have been reviewed but are not included in Table 1 for two reasons: some of them do not specify how RF are calculated, while others focus on furrow irrigation in rice crops located in Asia, where DI is not an option (Do et al., 2020; Hervás-Gámez and Delgado-Ramos, 2020; Pakhtigian et al., 2020; Pérez-Blanco et al., 2020).

4. Materials and methods

This section includes the description of the case study in the Guadalquivir River Basin (Southern Spain) and the analytical framework, where net irrigation requirement, relative water supply, *E*, and an economic optimization are calculated, following the methodology outlined in Fig. 2, for the analysis of the overestimation of RF. Table 2 specifies all data sources used in the analysis. Data sources in Table 2 are numbered and correlated by the numbering with the calculation flow diagram (Fig. 2). Calculations within the diagram follow the framework described in the next subsections.

4.1. Case Study in Southern Spain

Although the analysis presented in this study could be applied to many other case studies, in this paper we focus on the Guadalquivir River Basin (Southern Spain), exploring the basin-level impact of widespread adoption of DI in this representative Mediterranean basin as an illustrative example.

Over the years, DI has become widespread in the Guadalquivir Basin and has been documented as an adaptation strategy to drought episodes (Lorite et al., 2007). Besides temporary drought situations, the trajectory of the water balance in the Guadalquivir basin has led to a structural deficit in which demand exceeds supply and adaptation is achieved by the application of DI to some crops; specifically, winter cereals, some

Table 1
Sample of hydro-economic models providing detail on return flow calculation.

Basin	Applied Water Use Efficiency Coefficient	Irrigation Return Flows	Hydro-economic model
Ebro (ESP)	Flow continuity equation in the basin: $Win_{d+1} = Wout_d + r_d^{IR}$ $(Div_d^{IR}) + r_d^{URB}$ $(Div_d^{URB}) + RO_{d+1}$. Where r_d^{IR} (Div_d^{IR}) are the RF from upstream irrigation districts, and r_d^{IR} is a factor depending on the crop and the type of irrigation technology applied on the plot.	Set constant for each crop and technical irrigation system.	(Baccour et al., 2021)
Africa	Average *E* in Africa is 42 %	Fixed global	(Kahil et al., 2018)
Jucar (ESP)	Flow continuity equation in the basin: $Win_{d+1} = Wout_d + r_d^{IR}$ $(Div_d^{IR}) + r_d^{URB}$ $(Div_d^{URB}) + RO_{d+1}$. Where r_d^{IR} (Div_d^{IR}) are the RF from upstream irrigation districts, and r_d^{IR} is a factor depending on the crop and the type of irrigation technology applied on the plot.	Set constant for each crop and technical irrigation system.	(Kahil et al., 2016)
Thessaly (GRC)	Irrigation method efficiency estimated from a field survey.	Set constant for each crop and technical irrigation system.	(Alamanos et al., 2020)
Volta (Africa)	From a certain annual depth of applied irrigation water required for any given crop, an ET is set in the process of growth, as well as information on *E*. The difference, water applied minus ET, is what returns to the system, typically either the aquifer or to a stream or river. Parameter Bu_p (Crop water demand, divert, use and return).	Set constant for each crop and the technical irrigation system.	(Baah-Kumi and Ward, 2020)
General application model	Water withdrawal is calculated using the water efficiency rate provided by (FAO, 2012) and (Frenken and Gillet, 2012).	Set constant for each crop and technical irrigation system.	(Burek et al., 2020)
Rio Grande (USA-MEX)	From a certain annual depth of applied irrigation water required for any given crop, an ET is set in the process of growth, as well as information on *E*. The difference, water applied minus ET, is what returns to the system, typically either the aquifer or to a stream or river. Parameter Bu_p (Crop water demand, divert, use and return).	Set constant for each crop and technical irrigation system.	(Ward et al., 2019)
Salton Sea (USA)	Drainage D can be expressed as functions of w that depend on a number of crop and system parameters, including the potential crop transpiration rate, T_P; the amount of direct evaporation, E; the salt tolerance of the crop, EC_{50}; the salinity of the irrigation water, EC_{IW}; and the fraction of applied water that runs off the field as tail water, t_f. D(w) $D(w;\ T_P,\ E,\ EC_{50},\ EC_{IW},\ t_f)$.	Set constant for each crop and technical irrigation system.	(Levers et al., 2019)

(*continued on next page*)

Table 1 (*continued*)

Basin	Applied Water Use Efficiency Coefficient	Irrigation Return Flows	Hydro-economic model
Tajo (ESP)	Data provider for water withdrawals and irrigation technology (Tajo River Basin Authority, 2014).	Set constant for each crop and technical irrigation system.	(Pérez-Blanco et al., 2021)
Helleh River (IRN)	Water demand of an agricultural demand site in year y and season t equals $\sum_{u=1}^{U(i)} A_{i,u,y} IR_{i,u,y,t} / \mu_{i,u}$, where µ is an *E*.	Set constant for each technical irrigation system.	(Aein and Alizadeh, 2021)
Montana (USA)	This model assumes 70 % efficiency in the water conveyance system and the irrigation technology.	Fixed global	(Maneta et al., 2020)
Murray-Darling Basin (AUS)	The following equation is an accounting relationship describing the destination of irrigation water applied; part of the applied water is consumed by crop: $f_{ij} = \alpha (W_{ij} - CW_{ij})$, where α = a fraction, the difference between applied and consumed water	Set constant for each crop and technical irrigation system.	(Qureshi et al., 2010)
Guadalquivir (ESP)	Return flows, Xr, at each return flow node, r (a subset of i), is the proportion of the water applied, Xa, that returns to the river system. RF are defined as follows: $X_r = \sum_a b_{a,r} * X_a, \forall r$	Set constant for each crop and technical irrigation system.	(Martínez-Dalmau et al., 2023b)

Source: By the authors.

An overall conclusion of searched literature is that all those hydro-economic models (Table 1) assume constant returns as a function of RF = W(1-E_0) and assume constant E_0 instead of a variable E, and this simplification results in an optimistic overestimation of available resources.

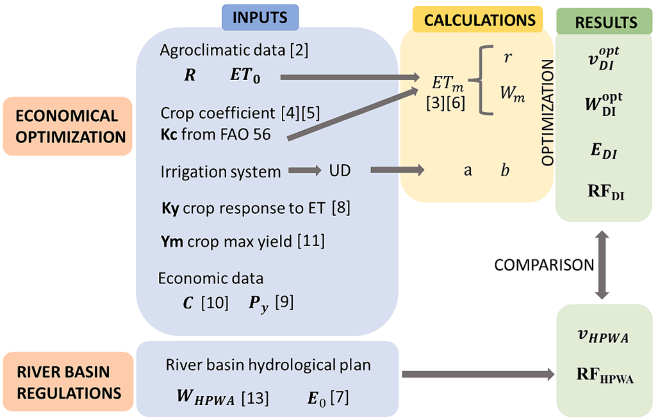

Fig. 2. Calculation flow for the agronomic and economic variables, economic optimization, and comparison with the river basin regulations.

industrial crops and olive trees, which are irrigated below maximum yield requirements.

This adaptative strategy has gone beyond a response to drought and has become a specific feature of the Guadalquivir Basin, as noted by Fernández García et al. (2014), who conducted an empirical analysis of a group of Water Users Associations (WUAs) covering 36,000 ha. Their results showed that most of the WUAs have *ν* values structurally below unity. Tocados-Franco et al. (2022) examined the evolution of land use in the basin, concluding that the increase in irrigated area and perennial crops results in an overall decline in *ν*.

Table 2
Data sources used in the analysis.

	Data Description	Source
[1]	Area of irrigated crops present in the Guadalquivir basin years 1989, 1999, 2004, 2007, 2012.	(Instituto Nacional de Estadística, 2020)
[2]	Average monthly precipitation (P) and reference evapotranspiration (ETo) from annual series 2002–2022, 21 years. Average was calculated from data of the agroclimatological stations located within the Guadalquivir basin, 56 stations in total.	Own estimation with Andalusian Agroclimatic Stations (Junta de Andalucía, 2023c) Available at: https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web/
[3]	Share of trees intensity for irrigated olive	(Junta de Andalucía, 2023b)
[4]	Crop coefficient (Kc) for determination of evapotranspiration in olive orchards	(Orgaz and Fererez, 1997)
[5]	Crop coefficient (Kc) for determination of evapotranspiration in the remaining crops	(G Allen et al., 2006)
[6]	Irrigation needs estimation. Own estimation with single Kc following FAO56 methodology. Water retention for the water balance is considered as the retention for an average loam soil.	(G Allen et al., 2006)
[7]	Efficiencies assumed for the irrigated systems in the Guadalquivir basin. There is a different efficiency adopted for each irrigation technique. Standard irrigation efficiency (Eo) as a fixed value based on the irrigation system (furrow, sprinkler, drip) obtained from regulations in the Guadalquivir basin	Obtained from CHG (2023), the last available River Basin Management Plan, 2022–2027
[8]	Coefficient of crop yield response to ET (Ky)	(Steduto et al., 2012)
[9]	Crop sale prices. Year 2022	Own estimation based on Ministerio de Agricultura Pesca y Alimentación – ECREA network (2022) and Junta de Andalucía, (2023a)
[10]	Production cost. Year 2022	Own estimation based on Ministerio de Agricultura Pesca y Alimentación – ECREA network (2022) and Junta de Andalucía, (2023a)
[11]	Maximum crop yield	(Ministerio de Agricultura Pesca y Alimentación, 2022)
[12]	Irrigated crops area in the Guadalquivir basin	Obtained from CHG (2023), the last available River Basin Management Plan, 2022–2027 and Martínez-Dalmau et al. (2023b)
[13]	Water allocation for different crops in the Guadalquivir basin	Obtained from CHG (2023), the last available River Basin Management Plan, 2022–2027

Source: By the authors.

The evolution of *ν* in the basin since the year 2000 (Fig. 3) shows a slight decrease in the water supply (quotas), with a further reduction during drought years (2000, 2005–2008, 2020-present). Meanwhile water rights are scaled back as a response to increasing *E* through drip irrigation systems, and conveyance losses are reduced through a modernization strategy. Unfortunately, *E* gains are usually accompanied by a change in crop patterns, with an increase in perennials and water-intensive crops, meaning that net and gross irrigation needs increase (see trend line in Fig. 3). The combination of increasing water demand and decreasing water rights results in a drop in *ν* over the analysed period. The *ν* varies from a minimum of 0.31 (year 2008/2009) to a maximum of 0.90 (year 2012/2013), with a global average of 0.58 for the complete period 2000–2021, but if drought years are not considered, the average *ν* is 0.66.

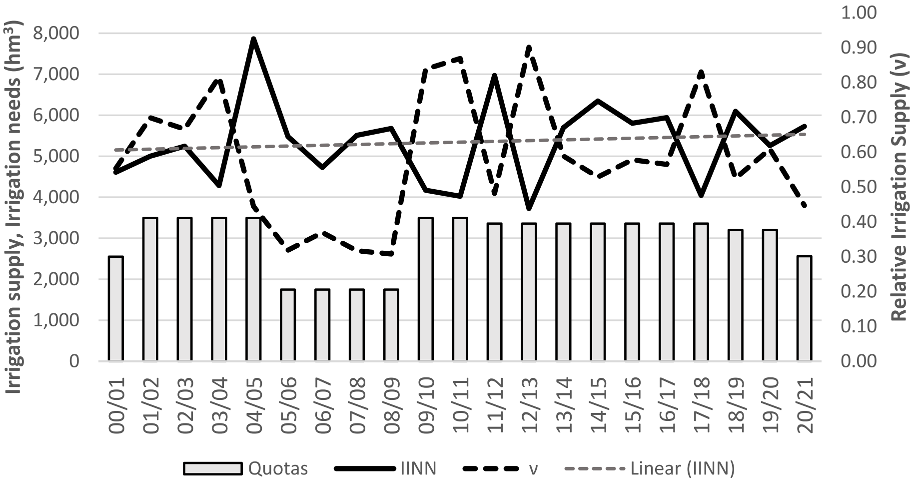

Fig. 3. Annual water supply for irrigation (quotas), irrigation needs (IINN) and relative irrigation supply (ν). Source: Water Agency (Confederación Hidrográfica del Guadalquivir), irrigation needs and relative irrigation supply (ν) own estimation based on (Tocados-Franco et al., 2022).

4.2. Analytical framework: net irrigation requirement, relative water supply, and irrigation efficiency

This section presents the model that relates the main parameters of irrigation water with the aim to link the water supply, evapotranspiration and RF to a context with DI doses. This could also have been done with some models available in the literature that assume quadratic water production functions (WPF) such as the pioneering model of English (1990) and Martin et al. (1989) that has been expanded by Trout et al. (2020) or by using a Cobb-Douglas power curve relationship (Martin et al., 1989). When WPF is continuous as the mentioned quadratic or Cobb-Douglas functions, the analytics is simplified. We have selected an alternative WPF that assumes linear response between ET and Yield and that have been widely documented in agronomic science. The use of ET has many advantages and there is abundant information of crop (Y-ET) response functions, that specifically simulates yield 'Y' as a function of ET. The disadvantage of this linear approach is the analytical complexity of analytical solutions caused by the discontinuity of the WPF that implies that Y-ET need to be modelized in three different regions as we will see in Eq. 3 below.

According to overwhelming evidence from empirical research, the yield (*Y*) response to crop *ET* can be expressed as in Doorenbos and Kassam (1979). *ET* can be defined as the effective rainfall plus the variation in soil water storage during the crop growing cycle, the applied irrigated water, and the *E* (Berbel et al., 2018), as expressed in Eq. (1).

$$\left(1-\frac{Y}{Y_m}\right) = K_y\left(1-\frac{ET}{ET_m}\right) = K_y\left[1-\frac{E\hat{A}\cdot W+R}{W_m+R}\right] \tag{1}$$

where Y is actual crop yield; Y_m is the maximum crop yield; ET is actual evapotranspiration; ET_m is maximum evapotranspiration; K_y is the yield response factor between relative yield loss and relative reduction in ET; R is the effective rainfall plus the variations in soil water storage during the crop growing cycle; W is the applied (or used) irrigation water; E is the irrigation efficiency; and W_m is the net irrigation water requirement for a maximum yield (i.e. $W_m = ET_m - R$).

Irrigation efficiency, as previously stated, is understood as the irrigation water that is stored in the soil, (in the root zone), ready to be evapotranspired divided by the applied irrigation. E is related to actual evapotranspiration, effective rainfall, and the applied irrigation water ($E = (ET - R)/W$).

In Eq. (1) the variations in soil water storage during the crop growing cycle are included in R. This component of the global balance may be relevant for irrigation scheduling and crop management in Mediterranean environments. In any case, the adoption of a long-term approach that is valid for hydrological planning and water rights allocation is presented in the next section. As an innovation, this method was applied to a real-world hydrological basin, the Guadalquivir Basin (southern Spain), to analyse the relevant role of DI in the system.

Eq. (1) can be written with non-dimensional variables as expressed in Eq. (2):

$$y = \frac{Y}{Y_m} = 1 - K_y + K_y\frac{r+E\nu}{1+r} \tag{2}$$

where ν is the ratio $\nu = W/W_m$ and is called Relative Irrigation Supply, frequently noted as RIS; the relative yield (y) is the ratio $y = Y/Y_m$; and r is the ratio $r = R/W_m$.

The irrigation water to be supplied to allow optimal crop development is defined as W_m; for most crops and most climatic regions (such as Mediterranean basins) it can be assumed equal to potential evapotranspiration minus the effective rainfall.

The E relationship is critical to the optimization results. E depends on the application uniformity and RIS (ν). The analytical framework to build a model that relates irrigation doses with ET, E and RF is based on models frequently used in the irrigation science. Wu (1988) proposed a linear cumulative frequency distribution function used as an approximation of the water distribution in the soil to describe the irrigation scheduling parameters: percent of deficit, application efficiency and coefficient of variation by simple mathematical equations. Assuming the application follows a uniform frequency distribution, E can be calculated as expressed in Eq. 3 (Wu, 1988).

Equation 3 defines the different cases for the inverse of ν plotted against the wetted area fraction, assuming a uniform frequency distribution of the applied water. A detailed explanation of the application of the Wu (1988) method to this case can be found in Berbel and Mateos (2014), where basic elementary geometry is used to write the uniform frequency distribution in terms of the 'a' and 'b' parameters. The three regions of the Y-ET function are presented in Eq.3, defined as: (3.a) when all the irrigated plot is under DI, i.e., there is no fraction of the irrigated area that reaches full water requirements W_m dose; (3.b) part of the irrigated plot has reached W_m but part is still under DI scheme; (3.c) all the plot has surpassed the W_m threshold.

$$E = 1\frac{1}{\nu} > a + b = 2 - a \tag{3a}$$

$$E = \frac{(a\nu+1)^2 - 4\nu}{4(a-1)\nu^2}a < \frac{1}{\nu} < a + b = 2 - a \tag{3b}$$

$$E = \frac{1}{v}\frac{1}{v} < a \tag{3c}$$

where parameters ‘a’ and ‘b’ are related ($b = 2 - 2$a) and represent the distribution uniformity (DU) of the applied ater (e.g., for sprinkler systems, a common value of these parameters would be a = 0.80; b = 0.40).

Distribution uniformity and E are related although they represent different aspects of the system’s performance. DU measures how uniformly the water is applied to the plants or soil throughout the entire field. In this model, DU is a constant parameter that depends on irrigation system performance. E represents the effectiveness of an irrigation system in delivering water to the root zone of plants compared to the total amount of water applied, in this model ‘E’ is not constant and is a function of irrigation dose (W) and the level of DI, according to Eq.3 expression. Both are expressed as percentage. DU is a characteristic of the system, in this modelling activity DU was assumed 70 % for furrow, 85 % for sprinkler and 95 % for drip irrigation.

4.3. Analytical framework: Economic optimization

The economics of water use when water is the scarce resource and land is unbounding is developed fully in Berbel and Mateos (2014). A complete model that includes the allocation of water to land with the aim of optimizing farmers’ total profit responds to an objective function to be maximized. The critical assumptions are that farmers behave rationally and wish to maximize total net income. In particular, the focus of this article is on the basin and the overall consequences of microeconomic (farmer) profit maximization. When rainfed land is not productive (or profit is close to zero), the profit function is as follows:

$$\pi = A\hat{A}{\cdot}Z = A\hat{A}{\cdot}\left[P_y Y - P_w W - FC\right] \tag{4}$$

where Z is the profit per unit area, A is the irrigated area, P_y is the sale price of the crop, P_w is the price of water, and FC represents fixed costs per unit area. The value of A is determined by the total volume of available water V:

$$A = \frac{V}{W} \tag{5}$$

The optimal water use is defined by the maximum of Eq. (4) for the value of W that satisfies the equation:

$$-A{\cdot}\frac{\partial Z}{\partial W} = Z{\cdot}\frac{\partial A}{\partial W} \tag{6}$$

which can be transformed into (see Berbel and Mateos, 2014 for derivation):

$$v_{DI}^{opt} = \frac{W_{DI}^{opt}}{W_m} = \frac{K_y}{2(1-a)\hat{A}{\cdot}(1+r)\hat{A}{\cdot}\left(1-\frac{FC}{P_y Y_m}\right)+K_y a} \tag{7}$$

where v_{DI}^{opt} is the optimal relative irrigation supply for DI, W_{DI}^{opt} is the optimal irrigation supply for DI, and the rest of the parameters have previously been defined in this paper (see Berbel and Mateos, 2014; Wu, 1988 for additional details).

According to eq.7 the water price is not included in the DI optima, implying that water demand is totally inelastic to price changes at DI solution. Graphically, water demand becomes vertical in the DI solution and crosses the standard water price demand curve that is equal to Marginal Value of Water (MgWV) for values of water consumption that are lower than optimal DI. This inelasticity of water demand under DI conditions is consistent with farmers observed behaviour and has been documented by Fraiture and Perry (2007) and Expósito and Berbel (2016). Obviously, according to predictions of economic theory (Young and Loomis, 2014), the response curve to rising water prices has a negative slope when water use is lower than DI solution (alternatively, water price is higher than MgWV). Nonetheless, the model suggests that there will be no discernible response in the vertical segment (DI solution) if water prices are below MgWV value for achieving optimal DI, that behaves as a threshold for farmer response to water price (see Fraiture and Perry (2007) and Expósito and Berbel (2016) for further explanation and empirical findings).

The use of optimal DI solutions allows us to see the maximum profit for different crops. In Eq. (7) some parameters have a small range of agronomically possible values; for example, Ky is usually in the range from 1.0 to 1.25, while parameter ‘a’ goes from 0.60 (furrow, DU = 0.70) to 0.93 (drip, DU = 0.95). The most sensitive parameters are: (i) ‘r’, which is the ratio R/W_m and can range from very low values close to zero, to very high values in crops such as winter cereals, with a value over 3 in our selected case study (Guadalquivir Basin); and (ii) the cost structure, specifically from the ratio of fixed cost to maximum crop income $\left(\frac{FC}{P_y Y_m}\right)$.

4.4. Analytical framework: Overestimation of return flows in the basin

Return flows are computed as ‘RF = W(1-E)’ with efficiency (E) defined by Eq. 3. Understanding RF as return flows to the hydrological system. This simple approach for RF calculation, does not account for other interactions with the water table, where water can be directly incorporated to the water balance, by processes different than irrigation, such as capillary, but these processes are not common in water deficit basins like the Guadalquivir River Basin.

It should be noted that, contrary to what is often believed, E is not a constant value but rather a variable function of W, ET and R. Optimal DI water use (W_{DI}^{opt}) is used to estimate global basin efficiency taking into consideration field efficiency under DI computed according to Eq. 3.

In many cases, such as the Guadalquivir River Basin Hydrological Plan, E is used as a constant value, which we denote by E_0, the ‘standard irrigation efficiency’ (e.g., E_0 for drip irrigation is often assumed to be 0.95). E_0 is the E when actual evapotranspiration is equal to ET_m, and relative yield (y) is equal to unity. This study compares economic optimal results with the results based on the E_0 that is used in Spain for computing water balances. The official regulation is set by the relevant Ministry in the instructions for basin planning (Ministerio de Medioambiente, 2008). The Water Agency (CHG) selects the standard efficiencies for the whole basin (Eo) within the range given by Ministry for Ecological Transition and the Demographic Challenge (CHG, 2023), resulting in: furrow: $E_0 = 0.78$; sprinkler: $E_0 = 0.83$; drip: $E_0 = 0.95$. In the Guadalquivir River Basin Hydrological Plan, the latter values are used specifically to estimate RF (CHG (2023) Annex 2–4).

5. Results

Yield response to v varies under different K_y, r, and DU values. Different values of DU can be associated with drip, sprinkler, and furrow irrigation. Fig. 4 compares the response of y to v under three DU values for the same K_y and r values, showing that maximum yield is achieved at different v values, but in all cases v is above $v = 1$.

Calculations are made considering DU = 0.70 and $E_0 = 0.78$ for Furrow; DU = 0.85 and $E_0 = 0.83$ for Sprinkler; and DU = 0.95 and $E_0 = 0.95$ for Drip irrigation systems.

Fig. 5 shows that E is not constant, as is usually assumed by hydrological models that use the E at maximum yield as the standard value to estimate losses and RF when water balances are computed. The horizontal lines show the ‘constant’ value of E_0 for different irrigation systems used in the Guadalquivir River Basin Hydrological Plan. For example, for Furrow, for a v between 0.7 and 0.90, $E > E_0$ and for $v < 0.77$, $E = 1$, and therefore, there is no return flow.

Fig. 6 illustrates that return flows RF_0, understood as the amount of water not consumed (now expressed in parts per unit), when E is considered as a fixed value (E_0), differ notably from RF when E is

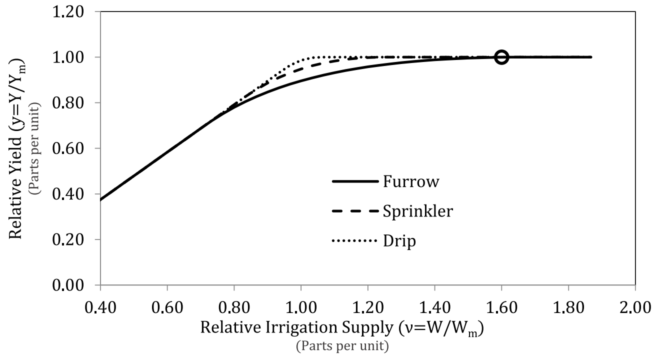

Fig. 4. Relative yield response (y) as a function of relative irrigation supply (ν) for a crop under different irrigation systems. Example: For $K_y = 1.25$ and $r = R/W_m = 0.2$, when furrow irrigation is used ($DU = 0.7$), maximum yield is achieved for $\nu = W/W_m \geq 1.63$ (denoted by a circle in the figure).

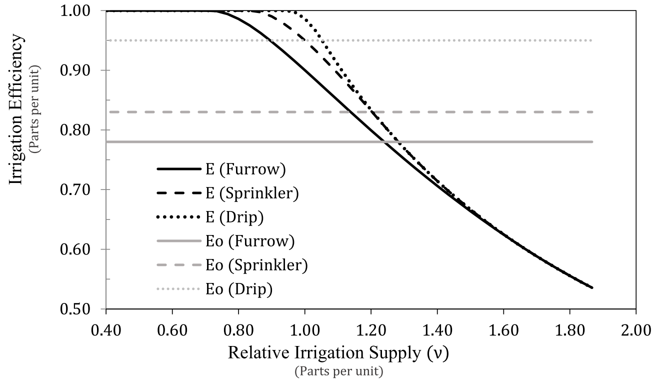

Fig. 5. Irrigation efficiency (E) as a function of relative irrigation supply ($\nu = \frac{W}{Wm}$) for a crop under different irrigation systems, and associated RF. Example is given for $K_y = 1.25$ and $r = R/W_m = 0.2$.

considered a variable function. It is important to note that RF are zero or close to zero when the crop is under major DI.

The outstanding result in this exercise is that irrigation losses (and the associated RF) for low values of ν are null (i.e., ν below 0.77 for furrow irrigation). This value indicates the level of DI in the crop. In case that DI practice is not accounted for hydrological models, the result will be an overestimation of RF, with the consequent risk of the available resources being overestimated and consequently overallocated.

5.1. Economics of irrigation water use

Following the economic optimization, three arable crops in a typical Mediterranean climate have been parameterized: maize, wheat, and sugar beet. Fig. 7 shows the evolution of economically optimal DI (Eq.7) for maize, sugar beet and wheat under a parameterization of the fixed cost to maximum income ratio.

Fig. 7 illustrates that the current economic optimum for maize (point A) is above its Relative Irrigation Supply, $\nu = 1.16$, pushing the solution towards full irrigation. However, for sugar beet (point B) and wheat (point C), the lines show how the ratio FC/P_yY_m pushes the solution towards DI, a low fixed cost generally points to a solution with higher DI (lower ν). The horizontal line in Fig. 7 shows the threshold W/Wm = 0.87 under which the calculated efficiency equals the unity (E = 1) for the crops and irrigation system shown in Fig. 7; over this threshold, Eq. 3.b or 3.c should be applied.

We have applied the economically optimal DI solution indicated by Eq. (7) for the main crops in the basin, with the results shown in Table 3. Table 3 below shows results for the optimization as well as the main economic and technical parameters for different crops in the Guadalquivir Basin. The DU parameter 'a' is computed from the 'average standard system efficiency', which is used in the basin to characterize field efficiency for the selected crops.

Table 3 presents the following critical parameters: r is the ratio R/

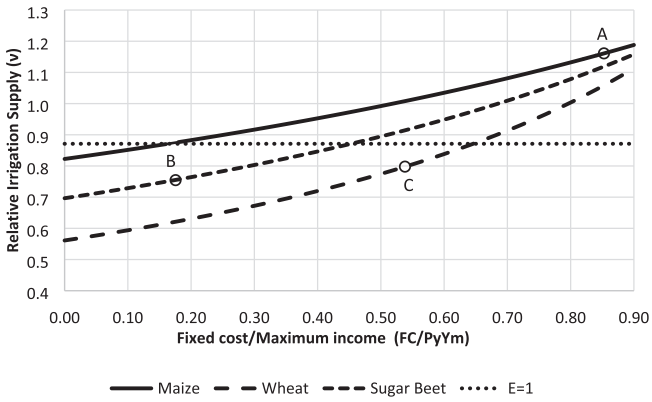

Fig. 7. Estimated relative irrigation supply at economic optimum with sprinkler irrigation (DU = 0.85) for maize (Ky = 1.25, r = 0.3) wheat (Ky = 1.05, r = 1.6) and sugar beet (Ky = 1.0; r = 0.6) with sale price 'P_y' and cultivation fixed cost 'FC' (year 2022) and agroclimatic context of the Guadalquivir Basin. The circles mark the optimal condition for each crop in 2022 economic conditions. The horizontal line indicates values of ν = W/Wm below which E = 1, for $\nu < 0.87$.

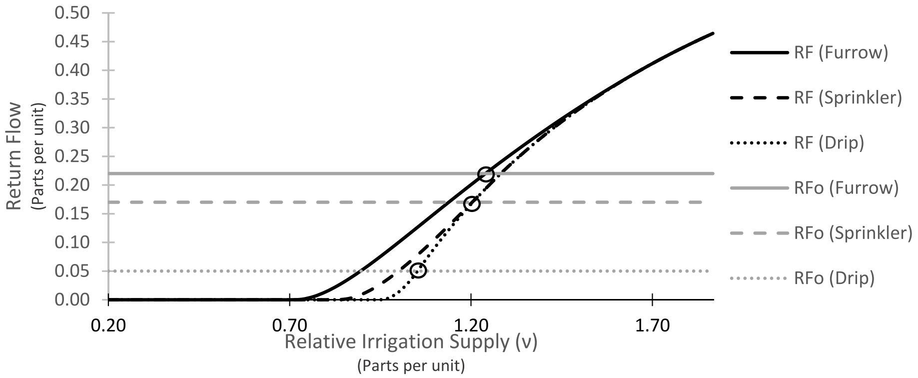

Fig. 6. Field distribution losses as a function of relative irrigation supply. Example is given for $K_y = 1.25$ and $r = R/W_m = 0.2$ (parameters that correspond to maize in a Mediterranean climate). The empty dots show the intersection of the two lines presented for each irrigation system, the horizontal line for a constant Eo, and another line for a variable E.

Table 3
Deficit irrigation economic optimum for selected crops in the Guadalquivir basin.

Crop	K_y	a	r	FC	Y_m	P_y	$W_m^{[1]}$	v_{DI}^{opt}	W_{DI}^{opt} [2]
Almond	1.15	0.93	0.54	2,249	2,500	4.00	688	0.93	642
Citrus	0.80	0.93	0.54	7,991	32,000	0.29	688	1.03	688
Cotton	0.85	0.80	0.29	700	2,550	0.49	717	0.94	673
Maize	1.25	0.80	0.30	3,304	12,500	0.31	695	1.16	695
Olive intensive	0.60	0.93	1.00	3,665	11,000	0.66	371	0.87	322
Olive traditional [3]	0.60	0.93	1.65	2,309	6,200	0.66	224	0.84	188
Sugar Beet	1.00	0.80	0.59	600	90,000	0.04	581	0.75	439
Sunflower	0.95	0.80	0.43	725	2,100	0.65	470	0.92	434
Wheat	1.05	0.80	1.58	904	4,000	0.42	234	0.80	187

Source: By the authors. Notes: [1] Wm was estimated with FAO methodology; [2] v_{DI}^{opt} and W_{DI}^{opt} were estimated with Eq. (7); [3] traditional olive groves characterized by a 7x7 tree density (205 trees $\cdot ha^{-1}$).

Wm for the basin and 'Wm' is the net irrigation requirement for maximum yield in mm for the basin in the same period; FC is the average fixed cost in EUR and P_y is the average crop sale price in EUR/kg, both for year 2022; Y_m is the maximum crop yield at full irrigation in kg/ha; v_{DI}^{opt} is the economically optimal v (also named RIS) for DI, and W_{DI}^{opt} is the economically optimal water use for DI in mm.

5.2. Overestimation of return flows to the hydrological system at the basin scale

The recommended economic optimum under DI for different crops is similar but on average higher to the 'administrative standard crop allocation' that the Water Agency (CHG, 2023) assumes for its Hydrological planning. Table 4 compares our economically optimal DI with the Water Agency crop allocations, obtaining v for the optimal solution and the current regulation.

It is important to note that GHPWA values presented in Table 4 correspond to the water rights entitlement that correspond to the maximum administrative allocation for each crop. Under drought conditions, W_{HPWA} values, and thus, the v_{HPWA} value will be lower. This depends on water availability in the basin, specifically to the water stored in the water bodies.

From Table 4, when the official allocation is compared to the DI optimum, the GHPWA for most of the crops is lower than the economic optimum (except sugar beet and winter cereals), as the Water Agency has relied on farmers' practices to try to match the scarce supply with the excess demand. Using the available resources, it is not achievable to supply the current irrigated area with W_m. Thus, the approach taken by the Water Agency is to use DI strategies to reach an equilibrium. Field efficiencies corresponding to these water supply volumes, as well as estimated RF for both cases (optimal and current situation) are shown in Table 5.

The standard efficiency values in the basin are selected within the range given by the Ministry of the Environment, as explained in section 2.4. Table 4 shows the estimates of optimal v for the whole basin calculated using Eq. (7) and Table 5 shows the corresponding efficiencies under DI estimated according to Eq. 3. Table 5 compares efficiencies estimated according to Eq. 3 with the standard irrigation efficiencies, E_0 considered in the river basin hydrological plan.

On average, basin crops have an optimal relative irrigation supply ($v_{DI}^{opt} = 0.88$) and associated efficiency of 98 %. This does not include some crops that cannot support DI such as (1) rice (36,158 ha) as it is irrigated by flooding, and thus DI is not an option; (2) vegetables, (22,929 ha) that have been excluded because of their variety and the

Table 4
Net irrigation requirement for maximum yield (Wm), economic optimum allocation, and Guadalquivir Hydrological Plan Water Allocation (GHPWA), and their respective relative irrigation supply.

		Water Supply (mm)			Relative Irrigation Supply	
Crop	Irrigated (ha)	W_m	W_{DI}^{opt}	W_{HPWA} [1]	v_{DI}^{opt}	v hpwa
Almond & fruits	49,387	688.4	642.5	600.0	0.933	0.872
Citrus	44,977	687.6	687.6	600.0	1.032	0.873
Cotton	53,796	717.3	672.7	562.5	0.938	0.784
Maize	20,284	694.6	694.6	625.0	1.161	0.900
Olive (traditional)	398,621	224.2	188.5	161.3	0.840	0.719
Olive (intensive)	97,009	371.5	322.2	226.3	0.867	0.609
Sugar Beet	4,410	581.5	438.8	562.5	0.755	0.967
Sunflower	32,630	469.9	434.4	313.3	0.925	0.667
Winter cereals	43,213	234.1	186.8	228.9	0.798	0.978
Total selected crops	**744,327**					
Average (weighted by volume)		**480.4**	**445.7**	**389.2**	**0.916**	**0.782**

Source: By the authors. Notes: Crop area and W_{HPWA} values are available in (CHG, 2023). Some crops not defined in the hydrological plan (i.e. "other herbaceous", 63,497 ha; "other woody crops" 29,103 ha), or not suitable for DI (i.e., rice, 36,158 Ha), have been excluded.

Table 5
Guadalquivir Basin efficiencies and returns flows according to hydrological plan and under deficit irrigation economic optimum.

		Computed DI Economic Optimum 2022			Basin Hydrologycal Plan (CHG, 2023)	
Crop	Irrigated (ha)	v_{DI}^{opt}	E_{DI}	Return (hm^3)	E_0	Return (hm3)
Almond & fruits	49,387	0.933	1.000	0.0	0.900	29.6
Citrus	44,977	1.032	0.964	11.1	0.900	27.0
Cotton	53,796	0.938	0.978	8.1	0.800	60.5
Maize	20,284	1.161	0.857	20.2	0.800	25.4
Olive (traditional)	398,621	0.840	1.000	0.0	0.800	128.6
Olive (intensive)	97,009	0.867	1.000	0.0	0.950	11.0
Sugar Beet	4,410	0.755	1.000	0.0	0.800	5.0
Sunflower	32.630	0.925	0.983	2.5	0.830	17.4
Winter cereals	43.213	0.798	1.000	0.0	0.830	16.8
Total selected crops	**744.327**			**42.8**		**321.2**
Average (weighted by volume)			**0.983**		**0.846**	

Source: By the authors. Notes: Crop area and E_0 values are available in (CHG, 2023); RF_{DI} = Return flows with DI solution.

difficulty that entails to calculate a generic W_m and compare it with generic W_{DI}^{opt} and W_{HPWA} values, which in any case would not be representative; and (3) other miscellaneous crops (poplars, vineyards, etc.) that amount to 78,489 ha, which were also excluded for their variety. The total irrigated cropping area in the Guadalquivir River Basin is 881,902 ha and this study gathers the situation for 744,326 ha, which represents the 84 % of the irrigated land in the basin. The primary practical implication for policymaking is that, assuming Guadalquivir Water Agency's estimations are accurate for the remaining 16 % of land, the correction of return flows through DI practice (as shown in Table 5) leads to an overly optimistic overestimation of available water resources by 278 hm^3. This overestimation amounts to 9 % of the recognized irrigation water rights within the basin (3202 hm^3 in GBHP 2022–27). This overestimation endangers water supply guarantee, particularly evident during the ongoing drought in the basin (since 2017). This drought has resulted in a reduction of water supply to only 18 % of the nominal water rights in the current season (2022–23).

Table 5 compares the field efficiency according to the economic optimum for DI computed with our model as v_{DI}^{opt} using Eq. (7). However, this table shows a large deviation in the estimates of RF depending on the efficiency value used, E_{DI} vs E_0. Fruit crops other than olive cannot handle deficits above 5–10 % as the fruit quality suffers, consequently having a negative effect on fruit sale price and farmer income. Some crops may adapt to regulated DI (Fereres and Soriano, 2007) but this requires precision irrigation which is not a technique widely used by farmers.

6. Discussion

There is a global consensus, among experts and water managers, that DI adoption impacts RF, although some water supply planning agencies do not incorporate this effect for water allocation, resulting in the overallocation of resources. This research contributes to this topic by quantifying the impact of DI adoption and comparing results with the basin regulation values, to give a quantitative estimation. To the best of our knowledge this is the first time that a quantitative estimation of effect of DI on RF has been done at basin scale.

Generally, hydro-economic and hydrological models have not incorporated the impact of DI practices into water resources accounts (see Table 1 above). Some models have indeed included survival doses for trees under drought conditions, such as in the study by Martínez-Dalmau et al. (2023a), where the reduced irrigation water doses have been modelled. Some models integrate farm behaviour under drought conditions that include a change in crop pattern (Pérez-Blanco et al., 2020), with farmers opting for less water-intensive crops to replace more water-intensive ones under water constraint conditions, but DI is still not modelled, and RF are assumed to be a constant percentage of applied water (RF = W(1-E)). Our model innovates hydro economic literature by considering RF variable as a function of climate, crops, applied water and level of DI. This study quantifies the impact on RF, at basin level, of DI adoption, based on an agroeconomic model of field efficiencies, which was developed to study the relationship between E and DI.

The trajectory of this basin has been carefully documented, highlighting how modernization through investment in water-efficient systems and DI practices has led to enhanced water productivity. This, in turn, has spurred an expansion in irrigated areas and agricultural intensification.

The rapid increase in irrigated land has created a situation where many farmers are unable to receive traditional full irrigation doses (Ym, Wm). Consequently, the Water Agency has stepped in to allocate water doses based on either 'common farmer practices' or specific studies. Surprisingly, our research has revealed that these water allocation mandates closely align with the DI optimal solution derived from the model.

At basin scale the results of the agroeconomic model show that RF are significantly overestimated when DI is widely adopted as water losses become null when ν is low. DI is often used when water supply is scarce, and farmers need to either reduce the irrigated area or reduce the water supply to the existing irrigated area.

The hydrological impact at basin level has been illustrated for the Guadalquivir basin, where it has been found that RF and water resources are substantially overestimated when using constant efficiencies that do not account for the impact of DI. In Guadalquivir, which is a typical Mediterranean basin, DI-corrected efficiencies, understood as the efficiency calculated for the economic optimum irrigation supply, give an average basin efficiency of 0.99 (RF = 0.01 %), a figure that is significantly higher than the one estimated by the Water Agency following the official Ministry protocol (average efficiency of 0.835, 16.5 % losses).

Losses or 'irrigation RF' are integrated into the water balance when estimating the water resources to be allocated to different users (environment or economic agents). The excess in the Guadalquivir basin 'standard constant return estimations' relative to the 'optimal DI-corrected returns' is 15.5 %. This figure represents a gross overestimation with a significant impact when a basin is over-allocated and therefore all available water resources are already exploited. If an 'optimistic' overestimate of RF (e.g., standard constant efficiencies) were used for the water balances, in the case of Guadalquivir, this would mean that a non-existent 15.5 % of water resources would be included on the supply side.

The situation in the Guadalquivir basin also applies to the other southern basins in Spain. Furthermore, it probably applies (although data are scarce) to other water scarce regions such as MENA countries, Southern European and other arid regions of the world where farmers are using DI as an adaptation to the reduction in water resources.

There is excessive optimism about the role of E improvements, also referred to 'modernization'. Some authors have argued that there may be a 'rebound effect' (Perry and Steduto, 2017), while others claim that the rebound effect can be avoided if proper governance measures are implemented (Berbel and Mateos, 2014).

DI is closely related to modernization as farmers will try to keep all their water savings (reduced RF). Policy options should include strict controls imposed by the Water Agency to prevent farmers from using this saved water, either maintaining the same cultivated area but with intensified cultivation (e.g., double cropping) or increasing their irrigated area, sometimes using DI strategies. As we have seen, a combination of efficiency improvements and DI will result in reduced or zero 'losses', meaning that in practice farmers will be'appropriating' RF that were formerly included in downstream uses or environmental flows. This behaviour has been reported in some water stressed areas, such as Moroccan aquifers, where Molle et al. (2017) claim that "in the vast majority of cases (most notably the southern deficit basins) this translates into a worsening of the net balance of the aquifers".

The results presented in this study suggest that in water scarce regions where DI is a prominent technique, the resources that are calculated as RF and consequently considered an input into the system are overestimated. We highlight some conclusions that can be drawn from the model and its application.

In our opinion, the model has some limitations that require additional research, among them we may mention: First, we have modelled DI as a simplified technique, but many growers in this basin, target their irrigations to critical periods (Regulated DI or RDI) in this river basin. Our model does not account for these types of management and the impact would be probably to increase water productivity when compared to 'uniform DI'. This advanced technique requires specific agroeconomic models that are not the focus of our research and probably require additional field data. In any case, we believe that will produce similar results our model when RDI solutions are similar to unform DI in terms of water use, in case that water use is higher/lower than agroeconomic model DI solution the RF will be higher/lower that our estimations, but always that DI is applied RF will be lower that constant RF=(W(1-E)) assumption.

Second, limitation is that agroeconomic model is applied to the Guadalquivir River Basin, a Mediterranean highly regulated basin that serves as a potential representative of similar systems found across various continents. However, it is essential to validate the results in different climatic and institutional settings.

Third, we have used for modelling optimal DI decisions the Berbel and Mateos (2014) based on Wu (1988) and the well-known yield linear response to ET as captured by Steduto et al. (2012), but maybe convenient to test results with other DI response models such Trout et al. (2020) based on quadratic response and an alternative methodology to the used in this paper and compare both results with observed farmer behaviour and effects of alternative models on RF.

7. Conclusions

Farmers' use of DI practices will rise in the future as an adaptation to worsening water scarcity due to population growth and the related demand for food, the increasing water demand from other economic sectors, and a decrease in resources caused by climate change. While agronomic researchers have documented the impact of DI on water productivity and farm profitability, a proper treatment of the impact of DI at catchment level is needed, with a particular focus on RF.

We hope that our work will be useful to make policymakers and experts more conscious of the hydrological impact of the DI agronomic practice, and its impact at basin scale. We have illustrated the practical consequences for Guadalquivir basin, that is the most important basin in Spain in terms of irrigated area (25 %) and agricultural production in Spain concluding that accounting for DI corrected return flows will reduce available resources by 8 % vs. standard practice, which is a huge value for an already overallocated basin, this example may be of relevance for other water scarce regions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Abbreviations and symbols

a	parameter that represents the distribution uniformity of the applied water (b = 2-2a)
A	irrigated area (determined by the total volume of available water)
b	parameter that represents the distribution uniformity of the applied water (b = 2-2a)
DI	deficit irrigation
DU	distribution uniformity
E	irrigation efficiency
E_0	standard irrigation efficiency, used in regulations
ET	actual evapotranspiration
ET_m	maximum evapotranspiration
FC	fixed cultivation cost (per area)
ha	hectares
GHPWA	Guadalquivir Hydrological Plan water allocation
Ky	yield response factor between relative yield loss and relative reduction in evapotranspiration
MgWV	marginal value of water
P_w	water price (cost)
P_y	crop sale price
R	effective rainfall plus the variations in soil water storage during the crop growing cycle
r	ratio of effective rainfall to maximum irrigation requirements = R/W_m
RDI	regulated deficit irrigation
RF	return flows
RF_{DI}	return flows calculated considering deficit irrigation
RF_{HPWA}	return flows according to the hydrological plan water allocations
V	total volume of available water
W	applied (or used) water
W_{DI}^{opt}	economic optimum water use for deficit irrigation
W_m	net irrigation water requirement for maximum yield
WP	water productivity
WPF	water productivity function
WP_{SI}	water productivity per unit of irrigation supplied
WUA	Water Users Association
y	relative yield (Y/Y_m)
Y	actual crop yield
Y_m	maximum crop yield
Z	profit per irrigated area
ν	relative irrigation supply, also called RIS, $\nu = W/W_m$
π	profit function

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