Effects of the irrigation modernization in Spain 2002-2015

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Abstract

Regions and basins suffering from water scarcity have promoted the modernization of irrigation systems, defined as irrigation efficiency enhancement as a measure for the adaptation to a growing demand and a limited supply of water resources. In the period 2002-2015, Spain carried out an intense irrigation modernization process with the aim of achieving significant water savings and higher flexibility and to guarantee supply, among other favourable outcomes (e.g. environmental and socio-economic). Nevertheless, certain unfavourable effects of irrigation modernization also need to be discussed. This study analyses these effects in Spain based upon a DPSIR (Driving forces, Pressures, States, Impacts, and Responses) framework and a wide-ranging review of the existing empirical literature. Our findings are highly relevant to inform decision-makers in the planning of future irrigation modernization programmes worldwide.

Keywords: irrigation modernization; water conservation; water use; water consumption; rebound effect; water management.

1. Introduction

Many arid and semiarid regions of the world have long since entered a ‘mature water economy' phase characterized by a limited water supply and growing water demand with ever more competing uses (Randall 1981). Certain regions have gone beyond this phase, to the point where their river basins and/or aquifers have reached a closure status. Closure occurs when all resources are allocated or ‘over-allocated’ because of human intervention (Molle 2008). Examples of over-allocation can be found in many regions of the world: California (Owen 2014), the US High Plains (Scanlon et al. 2012), Australia (van Dijk et al. 2013), Spain (Expósito and Berbel 2017a), Syria (Aw-Hassan et al. 2014), and India (Mall et al. 2006), among others.

Water-saving measures usually appear in the water-policy arena once water-supply augmentation is no longer economically feasible (Mateos 2008; Mateos and Araus 2016; Playán and Mateos 2006). Public subsidies granted to irrigation modernization investments have been justified by multiple positive expected outcomes, with water savings as the main desired result, but also followed by other objectives, such as higher resource-use efficiency, maintenance of farmers’ welfare (and related rural development), improved water quality (e.g. reduction in diffuse pollution), and adaptation to climate change (e.g. increase in resiliency). These policy goals are in line with the environmental-policy principles established by the EU strategy for resource-use efficiency (European Commission 2011) and the Blueprint to Safeguard Europe's Water Resources (European Commission 2012).

Most Spanish territory has a typically Mediterranean climate, whereby cultivation relies strategically on irrigation. In Spain, irrigated agriculture accounts for 20% of the total agricultural area, consumes 75% of total water resources, and generates 60% of the total agricultural production and 80% of agricultural exports (MAPAMA 2017). It is a relatively prosperous economic sector, which explains why irrigated areas have increased at an average annual rate of 0.67% in the period 2002-2015 (MAPAMA 2017). Currently, despite the limited storage capacity of over 55 km^3 (MAGRAMA 2016), irrigation expansion has reached 3.6 million hectares, thus driving most of Spanish river basins towards a closure status (Expósito and Berbel 2017a) and aquifers to over-exploitation (Custodio et al. 2016). The 'mature stage' of the Spanish water economy has forced a new demand-management policy instead of the traditional supply-augmentation policy. The flagship of this new policy is composed of the various national programmes for irrigation modernization.

This paper analyses the impact of the irrigation modernization process in Spain (2002-2015), one of the largest irrigation modernization programmes undertaken anywhere in the world in recent decades. Several studies evaluated the irrigation sector in Spain before its modernization. For instance, Rodríguez-Díaz et al. (2004) benchmarked the performance of irrigation schemes in Andalusia (southern Spain) using technical and financial performance indicators, while Varela-Ortega (2007) presented a case in central Spain for the analysis of how water and agricultural policies may affect the conservation of aquatic ecosystems. Other studies have analysed the specific effects of the Spanish programme for irrigation modernization, such as those on energy consumption and water usage (Fernández-García et al. 2014) and on the quality of return flows (Jiménez-Aguirre and Isidoro 2018). López-Gunn et al. (2012) published a broader study and a warning about the unintended effect of the irrigation modernization program: the potential increase of irrigation water consumption derived from the improvement of application efficiency. Our paper builds upon this previous research by introducing a comprehensive analysis of the observed effects of the Spanish irrigation modernization process (2002-

2015), which benefits from hindsight (the last modernization program ended in 2015), new research, and an analytical framework that has been previously applied in Europe for the evaluation of environmental policies.

The methodology used in this study to assess the impact of the irrigation modernization process is based on the DPSIR analytical framework (Driving forces, Pressures, States, Impacts, and Responses) which has been validated not only by the European Environmental Agency to analyse the society-environment interactions in various contexts (Kristensen 2004), but also by the EU Water Framework Directive (WFD) to design the river basin Programme of Measures.

The paper is organized as follows: Section 2 describes the Spanish national programme for irrigation modernization. The following section uses a DPSIR framework to explain the process that led the Spanish government to implement such a programme and its derived effects. The paper continues with two further sections focused on the analysis of the effects observed in the Spanish irrigation modernization process. The last section summarizes the paper and presents several concluding remarks.

2. The Spanish national programme for irrigation modernization

The National Irrigation Programme (MAPA 2002) was born as the policy response to a severe drought event in the mid-1990s that had a drastic impact on the entire national economy, especially on agriculture. The plan aimed to modernize 1.1 million irrigated hectares in the period 2002-2008, by improving large transport infrastructures, collective distribution networks and on-farm equipment. A second prolonged drought (2005-2008) triggered the second and the third modernization waves, known as the Shock Plan for Irrigation Modernization (MAPA 2006) and Plan for Irrigation Improvement and

Consolidation (MAPA 2008), respectively. Both plans involved combined interventions in more than 2.3 million hectares with an investment of around EUR 7,600 million in collective irrigation networks and infrastructure (CAP-JA 2011; Naranjo 2010). Actual interventions exceeded the initial plans in terms of both surface area and total investment, by eventually improving 1.79 million ha (Berbel and Gutiérrez-Martín 2017) with public subsidies representing around 60% of capital expenses (CAP-JA 2011).

Initially, the objective of this ambitious programme was to achieve water savings by improving and modernizing existing irrigation infrastructure. However, three additional objectives were publicly declared in order to justify public financial support: a) to promote rural development, diversification of the economy, creation of employment, and to boost the competitiveness of irrigated agriculture by adapting production to market demand and to EU agricultural policy; b) to improve water quality by reducing agricultural diffuse pollution; and c) to adapt to climate change, thus improving the resilience capacity of the agricultural sector. Regarding the main priority, expected water savings were set at 2.7 km^3/year, which is a significant volume considering that total irrigation water use is approximately 17.0 km^3/year. Consequently, irrigation modernization and subsequent projected water savings became key issues in the 1st (2009) and 2nd cycle (2015) of Spanish river-basin management plans.

3. The DPSIR framework applied to irrigation modernization

The DPSIR framework describes the society-environment interaction as a chain of causal links starting with 'driving forces' (e.g. human activities, development of economic sectors) through 'pressures' (e.g. abstraction, pollution) on the physical, chemical, and biological 'states' of bodies of water, leading to 'impacts' on ecosystems, human health and the economy, which eventually lead to political or private 'responses' (Kristensen 2004). Irrigation modernization can be considered a 'public response' within the proposed DPSIR framework.

DPSIR analysis is cyclical rather than linear, as illustrated in Figure 1. The irrigation modernization process promoted by central and regional governments in Spain is multidimensional and has generated various effects, most of which are favourable, thus alleviating pressure on water resources. Nevertheless, certain unfavourable effects can also be identified, such as increased water consumption (also known as the rebound effect) and higher energy use. As further explained in Sections 4 and 5, these observed effects have led to subsequent DPSIR cycles as shown in the same figure. These subsequent DPSIR cycles following the irrigation modernization process (as a response in the primary DPSIR cycle) are determined by the new drivers, pressures, status changes, impacts and responses. All these new cycles can be understood as the various effects derived from the irrigation modernization process in the case of Spain and elsewhere.

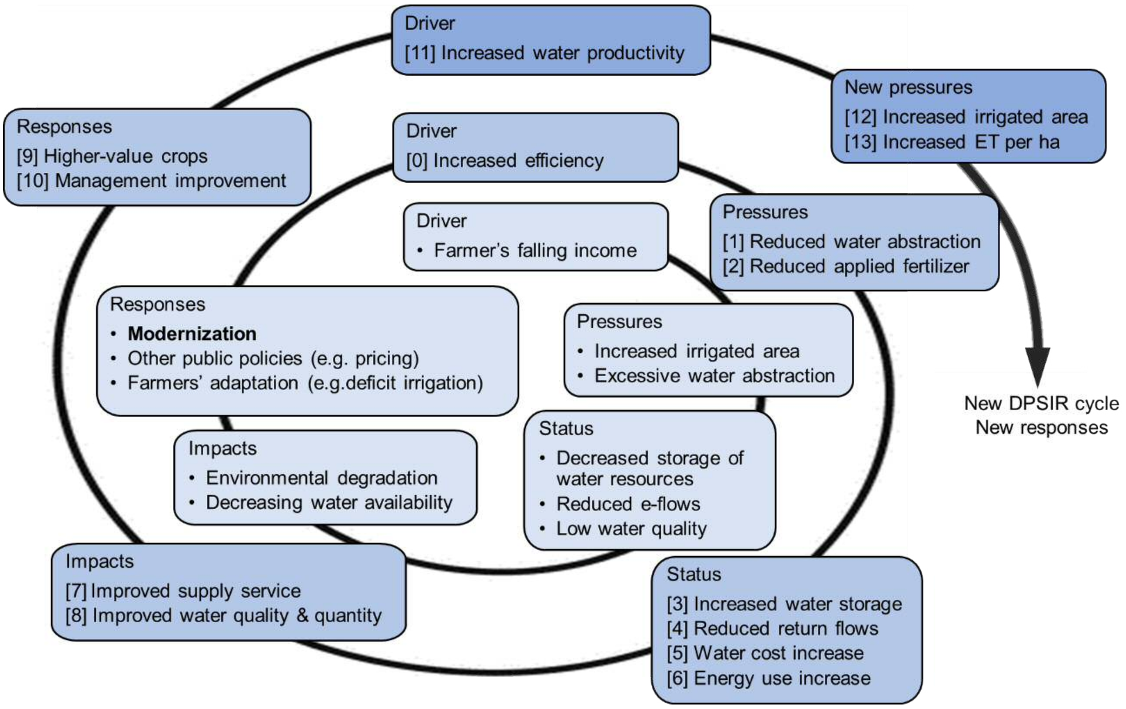

Fig. 1 DPSIR framework for dynamic irrigation modernization. Own elaboration

4. Favourable effects of irrigation modernization

The effects of irrigation modernization are multiple, occur on intersecting territorial and societal scales, and are closely interrelated. These effects take place on a local or basin scale and influence both the environmental and socio-economic context. This section analyses the most relevant favourable effects of the Spanish irrigation modernization process during the period 2002-2015.

4.1.Increase in irrigation efficiency

As a direct effect of the irrigation modernization process, irrigation water efficiency increases (described as a new driver in Fig. 1 [0]). Modernization is a public response to water scarcity and environmental degradation of bodies of water after an intensive irrigation expansion ('pressure'). The stated goal of the Spanish irrigation modernization programmes was that of achieving 'water savings' through a reduction in water abstraction by means of increasing irrigation efficiency (minimizing the runoff, percolation, and conveyance losses). This goal was achieved at basin scale, for example, Corominas and Cuevas (2017) estimate an increase in irrigation efficiency from 65% to 87% in the period 2005-2015 in Andalusia (southern Spain). Other researchers in Andalucía have verified the reduction of water used in irrigation schemes (Camacho et al. 2017; Fernández-García et al. 2014) as an indication of efficiency improvement. Reduction of water abstraction as a result of irrigation efficiency enhancement, while maintaining crop evapotranspiration, (ET), results in both a decrease of return flows (Fig. 1 [4]) and an increase of stored water (Fig. 1 [3]).

4.2.Reduced water abstraction

Water abstraction pressures are expected to reduce after modernization (Fig. 1 [1]). Water savings understood as reduced water withdrawal have been observed in irrigation schemes across the country; the Spanish Ministry of Environment estimated a reduction in the water diverted to agriculture from 17.8 km^3 in 2004 to 14.9 km^3 in 2015 (INE 2017). The results obtained by various studies carried out at Water User Association (WUA) level in various Spanish regions, whereby water abstractions are contrasted before and after the modernization process, include: a) Guadalquivir RB: -30% (36,000 ha survey, Fernández-García et al. 2014); b) Western Andalusia: -25% (90,000 ha survey, Borrego-Marín and Berbel 2017); c) Andalusia Region: -33% (from 1.1 million ha, Corominas and Cuevas 2017); d) Valencia Region: -40 to -60% (survey 60 WUAs, García-Mollá et al. 2017); e) Jucar RB, Acequia Real Jucar: -45% (35,000 ha, Estrela 2017); f) Tagus RB, Canal Estremera: -39% (29,000 ha, del Campo 2017). All these reductions are the result of the comparison of the water withdrawal before and after post-modernization. Furthermore, García-Mollá et al. (2013) also compare the reduction in modernized areas vs. non-modernized areas that are geographically closed and find that the reduction ranged from 50% in modernized areas to 25% in non-modernized areas, with the latter due to a stricter policy by the Water Authority. According to the published studies as quoted in the previous paragraph, the average reduction of irrigation water use in Spain was 33%. Nevertheless, under certain conditions, a ‘rebound effect’ in water use has also been identified; this is discussed later.

4.3.Reduction in fertilization use and improvement of water quality.

According to the DPSIR framework, the use of fertilizers by farms is considered a ‘pressure' with an environmental negative ‘impact’ when excess chemicals translate into diffuse pollution (Fig. 1 [2]). The average excess nitrogen from agricultural fertilizers in Spain is close to the EU average and is estimated at 20-25 kg/ha/year (MARM 2010). The goal of the modernization policy was mainly to reduce quantitative pressure (water abstraction); however, qualitative pressures have also been reduced. In this respect, Estrela (2017) notes that high-frequency localized fertigation improves fertilizer efficiency, and results in a 27% reduction in the applied fertilizer in modernized sectors of the Jucar river basin. Consequently, the cost of fertilizer has been reduced significantly on average, from 300-400 EUR/ha to 200 EUR/ha (López-Gunn et al. 2012), which has also helped to stabilise farmers’ income (DPSIR driving force).

A positive effect of the reduction in fertilizer application involves the improvement in water quality (Impact [8] in Fig. 1). This positive effect is generated by the combination of an increased efficiency in nutrient use (justified by more frequent and uniform applications) and a reduction of polluted return flows. Evidence is extensive in the case of Spain. García-Garizábal and Causapé (2010), Barros et al. (2012) and Jiménez-Aguirre and Isidoro (2018) show, in the case of the Ebro river basin, that improved irrigation efficiency has reduced both the volume of return flows and the amounts of nitrates and salts in the drainage ditches of two irrigation schemes. Along a similar line, López-Gunn

(2017) detected positive impacts of irrigation modernization on the water quality in the Duero basin (north-western Spain). For the Jucar basin (eastern Spain), Estrela (2017) cites a reduction of approximately 10% in diffuse nitrogen pollution at river-basin level due to modernization measures.

4.4.Improvement in water supply service: quantity, quality, flexibility

Irrigation modernization deploys positive effects in terms of an increase in water storage and an improvement of supply services in both flexibility and quality (Fig. 1 [3] [7] [8]). There is a complementary relationship between investment in water storage capacities and water-use efficiency (Xie and Zilberman 2018): water savings remain stored for future use, thereby improving the guarantee of supply. In this respect, Guadalquivir Hydrological Plan (CHG 2013) estimate that the probability of irrigation supply failure is reduced after modernization from 33% to 18%. Moreover, farmers and water users value the improved supply guarantee and certain studies (Mesa-Jurado et al. 2012) have reported relatively high willingness to pay for an increased guarantee of supply. Furthermore, the increased guarantee can be considered as a measure of adaptation to climate change since the forecast of the climate scenarios involves increased rainfall variability and more frequent drought events.

4.5.Increase in the cost of water

As a favourable result of the modernization process, more than 1.5 million hectares have implemented volumetric metering valves, thereby enabling the change from a traditional flat-rate pricing system (per land basis) to volumetric pricing based on binomial tariffs with a fixed part and a volumetric part depending on the volume of water used. This conversion to volumetric pricing has been argued by policy makers as being a necessary instrument of demand for the reduction of agricultural water consumption. Its effectiveness, however, remains a controversial issue (Berbel et al. 2018; Expósito and Berbel 2017b). Nevertheless, irrigation cost per water unit, as well as per hectare has increased (Fig. 1 [5]) due to the new pricing scheme and to other factors, such as the increased energy consumption (Fig. 1 [6]). Specifically, Sanchis-Ibor et al. (2017) estimate an 80% cost increase in Valencia (eastern Spain), from 515 EUR/ha to 927 EUR/ha, while in the case of Andalusia (southern Spain), Borrego-Marín and Berbel (2017) estimate an average increase of 128% (from 149 EUR/ha to 339 EUR/ha) for a sample of 9 irrigation schemes. Notwithstanding, the final impact of modernization on irrigation cost depends largely on the situation prior to modernization and the water source (surface or groundwater).

4.6.Increase in production value and water productivity

Irrigation water productivity is defined as the ratio of economic value generated per irrigation unit (estimated as gross value added per cubic metre). Ex-post analysis of the impact of modernization on agricultural value added in modernized areas generally shows that factor productivity (i.e. land, labour, water) has increased, mainly due to the higher value generated, but also, although to a lesser extent, to a reduction of input factors (e.g. water abstraction). Changes in cropping patterns have been accelerated by greater flexibility and reliability of the water supply, thus allowing the cultivation of high-value perennial crops (Fig. 1 [9]), such as citrus and olive trees, and replacement of commodities, such as cotton, maize, sugar beet and cereals (Expósito and Berbel 2017a). According to Castillo et al. (2017), the expansion of citrus and olive orchards in the Guadalquivir basin has been accompanied by a yield increase of about 10%, while no clear trend is observed in the case of commodity crops. Conversely, Lecina et al. (2010) find that maize yield has increased in the Ebro basin due to the modernization process. Furthermore, this shift to perennial crops of high value added may imply a loss in resilience against episodes of water scarcity as farmers have no room for manoeuvre using annual crops as a buffer as before, since they now use the water formerly devoted to annual crops in perennial or high value crops. This loss of resilience may be compensated by the higher quantity of water stored in reservoirs thanks to the decrease of water allocation due to modernization.

The modernization process is also behind the significant growth observed in the economic productivity of irrigation water (Fig. 1 [11]). Specifically, Expósito and Berbel (2017a) found that the mean irrigation water productivity in the Guadalquivir basin increased from 0.49 to 0.60 EUR/m^3 (gross value added at constant prices, base year 2012) in the period 2005-2012. This increase in water productivity may trigger a new cycle of water over-abstraction since incentives to use more water (crop intensification, and irrigated area expansion) may arise. The potential risk of increased extraction is based upon the fact that the value of water is a function of water physical productivity and output price. Given that modernization increases the value of water, a new cycle of water over-abstraction may take place. However, this potential risk, as mentioned by certain authors (Molle and Tanouti 2017), does not translate directly into larger withdrawals if proper water policy and governance is implemented (Perry et al. 2017).

4.7.Management changes

Social effects from irrigation modernization have probably received less attention in the literature than they deserve, even though they remain significant in terms of changes in water and crop management (Fig. 1 [10]). Castillo et al. (2017) find that crop changes towards perennial crops and higher cropping intensity are positively correlated with the participation of younger and more entrepreneurial farmers. Thus, irrigation modernization appears to be the engine driving this change, with the most enterprising farmers playing a pivotal role. Additionally, WUAs have required a higher level of professionalization of their human capital, with engineers and financial managers incorporated into their staff. Modernization has led to the entrance of highly-qualified human capital in the agricultural sector. Furthermore, Sanchis-Ibor et al. (2017) report that WUA mergers intensified due to the modernization process, which implies management efficiency gains and reduced operational costs.

In the long term, the effects of these internal changes should contribute towards sustainable rural development and farmers' welfare. In fact, the modernization process has brought with it other less tangible improvements in farmers' well-being. According to the irrigation district managers interviewed by Borrego-Marín and Berbel (2017), as part of the survey carried out by Castillo et al. (2017), modernized areas have improved their operational capabilities thanks to the on-demand operation, the automation and remote control of irrigation processes, and to a greater capacity for high-skilled job creation.

5. The unfavourable effects

Irrigation modernization processes may lead to increased pressures on water resources, triggering a second DPSIR cycle, as shown in Fig. 1. This section describes the two most relevant unfavourable effects of irrigation modernization: 1) higher water consumption; and 2) the increase in energy consumption.

5.1. Increased water consumption as a result of increased irrigated area and higher ET

The commonly-held belief that improving the efficiency of irrigation through high-tech agriculture would translate into water savings and a more sustainable use of the resource has been put in doubt by a wide variety of studies (e.g. Loch and Adamson 2015; Molle and Tanouti 2017; Perry et al. 2017; Scott et al. 2014). Some of these studies find evidence that irrigation modernization leads to higher water consumption as the irrigated area usually increases (increase in water use or abstraction) (Fig. 1 [12]) and/or changes in crop patterns lead to higher water consumption per unit area (Fig. 1 [13]) (Perry et al. 2017). This undesirable consequence in terms of an increase in the amount of water used and consumed is commonly known as the rebound effect.

The importance of the rebound effect has attracted the attention of not only scholars but also policy makers (European Commission 2012), the Food and Agriculture Organization (FAO) (Perry et al. 2017), and environmental groups. This section aims to review the evidence of the possible rebound effects of irrigation modernization in Spain under different conditions (pre- and post-modernization). The rebound effect has usually been explained by the fact that irrigation uniformity and efficiency improve crop evenness and productivity, and thereby increase evapotranspiration. Additionally, delivery flexibility and the possibility of using different irrigation methods facilitate crop diversification and enable a longer irrigation season, which may contribute towards an additional evapotranspiration increase. In certain cases, water that could have been saved thanks to a more efficient irrigation application is instead used to expand the irrigated area, further increasing resource depletion. Water-use irrigation efficiency is defined as the ratio of water consumed (mainly ET) to total water applied (Brouwer et al. 1989) and according this definition, the volume of water applied is reduced after modernization, although the result regarding basin consumption remains uncertain due the lack of detailed water accounting that impedes any precise calculation of savings.

In the specific case of Spain, four different scenarios can be highlighted regarding consumptive water use following modernization (Table 1).

Table 1 Classification of irrigation modernization scenarios in Spain

	Previous Deficient irrigation/ Water quota maintained	***Previous Full irrigation/ Water quota reduced***
Irrigated area maintained	Water use: Small reduction Water consumption: Increase *Alcón et al. (2017)*	Water use: Reduction in water abstraction (25-30%) Water consumption: No change *Fernández-García et al. (2014); García-Garizábal and Causapé (2010); García-Mollá et al. (2013)*
Irrigated area increased	Water use: Small reduction Water consumption: Increase *Lecina et al. (2010)*	Water use: small reduction Water consumption: No change *Scott et al. (2014); Corominas and Cuevas (2017)*

Source: Authors' own.

The first scenario (upper left-hand cell) is characterized by irrigation schemes under deficient water allocation (water entitlements below irrigation water requirements) before the modernization process begins, and the irrigated area is not enlarged. In this case, the improvement in irrigation efficiency has generally alleviated the deficit in crop water supply, thus moving towards full crop water requirements. Consequently, evapotranspiration (i.e. water consumption) has increased while water use has remained mostly unchanged. Alcón et al. (2017) report this outcome in areas of south-eastern Spain.

The second scenario (bottom left-hand cell) is characterized by irrigation schemes where the pre-modernization water allocation was theoretically at full irrigation supply, even though distribution and application efficiencies had deteriorated over the years. In fact, conveyance losses meant that water supply at the farm gate was below crop requirements. Therefore, as the first case, on-farm water supply was insufficient to meet crop irrigation requirements: crops suffered from water deficits and/or the irrigated area was less than the irrigable area. In this case, water use has remained unchanged and water consumption has increased. Such a situation was reported by Lecina et al. (2010) in the *Riegos del Alto Aragon* Irrigation Scheme (100,000 ha in the Ebro river basin, north-eastern Spain). The modernization of this scheme improved distribution efficiency and allowed surface irrigation to be replaced by sprinkler irrigation, thereby facilitating crop intensification and alleviating the crop-water deficit.

A third scenario (upper right-hand cell) is characterized by irrigation schemes where water supply was sufficient and irrigation efficiency improved after modernization. In this case, while water use has declined, it is uncertain whether consumptive use has decreased. Studies focusing on the Guadalquivir basin (Berbel et al. 2015), the Ebro basin (García-Garizábal and Causapé 2010), and the Valencia region (García-Mollá et al. 2013) generally report a decrease of approximately 25-30% in water use (abstractions). The reduction in water use due to improved irrigation may be accompanied by a small increase in ET if the enhanced systems result in better crops (Berbel et al. 2018). However, it is difficult to detect this effect in the irrigation schemes analysed in the studies cited above due to the complexity of the ET measurements and the interference of other factors during the modernization process.

Finally, the last scenario (bottom right-hand cell) represents those case studies where water savings have been used to expand the area irrigated (López-Gunn et al. 2012; Scott et al. 2014). Increased irrigated area implies more consumptive use. This can be attributed to the modernization programme itself and to the lack of control measures. In fact, the irrigated area in Spain has undergone continuous expansion (average 1% annual growth since 1990) independently of the modernization programme. The irrigated area expansion has been driven not only by agronomic and market factors (for instance, intensive olive oil farming and the production of vegetables and berries under plastic in southern Spain) but also by the emergence of technology that gave access to previously untapped water resources (i.e. groundwater pumping and its surface storage) and enabled precise water application (i.e. drip irrigation). In this context, a weak policy and control of groundwater use have led to this unfavourable effect, which surely has a greater impact than that caused by the modernization itself (Corominas and Cuevas 2017). Nevertheless, there is a need for detailed and proper water accounting either by means of a hydrologically detailed model or a wider analysis including economic variables such as in the System of Environmental-Economic Accounting for Water (Gutiérrez-Martín et al. 2017; United Nations 2012). The methodological problem involves the disentanglement of the expansion of the irrigated area that is triggered by water-conservation and water-saving technologies from the historical trend of irrigation expansion, where a worldwide annual growth in the area irrigated has been observed. This long-term trend is explained mainly through the different productivity of irrigated vs. rain-fed land.

5.2 Increase in energy use

Energy use in irrigated agriculture is becoming a serious global challenge for the coming decades worldwide since modernization usually leads to a change in the energy-use status (Fig. 1 [6]). In fact, flood irrigation systems in Spain involved no major energy consumption before modernization (0.02-0.15 kWh/m^3). Since 2002, the modernization process has resulted in a significant increase in the patterns of energy use, in the range of 0.28 to 0.68 kWh/m^3 for pressurized irrigation systems. In this respect, studies, such as those by Moreno et al. (2010) and López-Gunn et al. (2012), report significant increases (of 40-75%) in the energy costs of irrigation districts in central Spain due to the combination of increased energy consumption and increased energy costs. Other studies, such as that by Rocamora et al. (2013), estimate a 2.4-fold increase in the energy cost component from 2008 to 2010 due to modernization, while Rodríguez-Díaz et al. (2011) found that average energy consumption in modernized schemes increased to 0.41 kWh in the Guadalquivir basin, thus accounting for up to 30% of the total operating costs of WUAs. The literature reviewed features the following responses to the observed energy cost increase: a) WUAs have embarked on intensive energy auditing to reduce energy use in their irrigation systems; b) the government has included energy efficiency as a policy objective; and c) there has been increased academic and private research and innovation in the field of renewable energy for irrigation and precision irrigation equipment and technologies. Despite these responses, no reverse in the increasing trend of energy cost has yet been observed.

6. Discussion and concluding remarks

This study reviews the evidence published on the effects of modernization, both favourable and unfavourable, as relevant components (drivers, pressures, etc.) in the proposed DPSIR analytical framework. Although early studies focused on specific disciplines to analyse these effects, such as hydrology (Mateos 2008; Whittlesey 2003) and agronomy (Playán and Mateos 2006), this study has employed a multidimensional approach, and has also included socioeconomic variables (e.g. production value, water productivity, farmers' welfare) in the analysis. To this end, relevant effects derived from the Spanish irrigation modernization experience have been highlighted to inform future initiatives in Spain and worldwide. Moreover, in our opinion, certain issues deserve further discussion.

One relevant issue to be discussed is that of cost of irrigation efficiency enhancement or modernization policy. The core argument of the political response to the increasing pressures on scarce water resources has generally been based on publicly subsidized investments in water conservation technologies with the aim of reducing irrigation water abstraction. According to the studies reviewed, the estimated reduction in agricultural water withdrawal would be around 33%. This figure is close to those observed in other international experiences; for example, in the Australian Murray-Darling Basin (MDB), the government-funded water-recovery program forecasts that at least 50% of the water savings will be transferred to the government in the form of water entitlements. However, the fact that they have no baseline accounting of what was previously being lost precludes any precise assessment of savings. The estimated cost for the Australian government has been AUS$ 7,500 per 1,000 m^3, reaching water savings of 2,526 hm^3 at a cost of 0.66 EUR/m^3 (measured in terms of annual equivalent cost, AEC) (Grafton 2017). In Spain, water savings of 2,362 hm^3 implied an AEC of 0.59 EUR/m^3 (MAGRAMA 2016). Nevertheless, Corominas and Cuevas (2017) offer a higher cost in the case of Andalusia of 1.15 EUR/m^3 for total water savings of around 986 hm^3. Borrego-Marín and Berbel (2019) conducted a cost-benefit analysis of modernization policy estimating a cost-benefit ratio of 4.1/1 for the Guadalquivir River Basin. These figures provide reference values for modernization investments around the world, thereby providing decision-makers with a more accurate assessment of the gains derived from modernization processes in relation to their implementation costs.

Another critical issue to be addressed involves the potential ‘rebound effect’ acknowledged by European policy-makers and the research community. The recent FAO report based on 20 case studies from 14 countries concludes that “when properly accounted at basin scale, total water consumption by irrigation [after introducing modern technology] tends to increase instead of decrease” (Perry et al. 2017). In our opinion, the key issue is the decisive policy action required to prevent this undesired effect. The experience in Spain supports the FAO report regarding the risk of a rebound effect under certain conditions. However, it also suggests that the most significant increases in consumptive water use will derive from an expansion of the irrigated area rather than from an increase in evapotranspiration per hectare. Therefore, sound water planning and proper governance would prevent the rebound effect. Molle and Tanouti (2017) also reached this conclusion when assessing the Green Morocco Plan, which subsidizes both the conversion to drip irrigation and the expansion of intensive farming. Similarly, van der Kooij et al. (2017) stressed that the introduction of technologies to save water in upstream locations may entail a reallocation of water from downstream users to upstream users, leading to potential rebound effects at the basin scale. Nevertheless, it is worth noting that current data collection and reporting on water use and consumption at basin scale have significant limitations, thus water accounting and the resulting figures are often questionable. The deployment of new water monitoring networks with detailed data on water abstraction, aquifer piezometric levels, streamflow real-time data and the use of satellite data and remote sensing technologies will provide in the future more detailed information at different spatial and temporal scale, thus contributing to more accurate water balances. Only then, uncertainty about actual and potential rebound effects will be minimised and policy measures and decisions guiding future irrigation modernization will be scientifically substantiated.

On the positive side, the modernization process has responded to the new water management paradigm, and pays more attention to resource efficiency, water quality, and ecosystem conservation than to increasing water supply in response to demand increases. Diffuse agricultural pollution imposes a significant social cost, which is normally fully transferred to society via taxes, extra charges in urban water services, or environmental degradation. The studies addressing water quality in response to irrigation modernization in Spain all show positive trends. Additionally, the EU Common Agricultural Policy reform for the period 2014-2020 has stressed the importance of integrated water and land management, by encouraging the compatibility of agriculture and nature conservation through a cross-compliance system that includes environmental goals (Henke et al. 2011). Although the increase in the cost of water has marginalized some farming systems, it has promoted a more efficient use of energy (involving the use of renewables) and, indirectly, a more efficient use of water (Abadia et al. 2010; Corominas and Cuevas 2017). Energy audits have prompted more efficient pumping, reorganization of irrigation turns (Abadia et al. 2010; Corominas and Cuevas 2017) and the introduction of renewable energies (mainly photovoltaic, thus contributing towards the reduction in greenhouse gas emissions) (Mushtaq et al. 2013). These further responses may lead to a reduction of the intensity of energy use and, consequently, to a decrease in the cost of water.

This study has drawn attention to the most significant empirical findings regarding the effects of irrigation modernization in Spain with the aim of extracting learning outcomes that may help in the design of future irrigation modernization programmes both in Spain and worldwide. As discussed throughout this study, both favourable and unfavourable effects are observed after irrigation modernization. From a multidimensional approach based on a DPSIR analytical framework, this study has shed more light on these effects. Despite the high costs associated to these modernization programmes, water abstractions have been significantly reduced, and have helped to achieve a better environmental status of the bodies of water. Nevertheless, unfavourable effects can also arise if adequate policy measures are not enforced (e.g. irrigated area moratorium, implementation of volumetric abstraction counters and control measures, reduction of abstraction entitlements).

One possible ex-post solution to avoid rebound effect would be to impose direct caps on water withdrawals (i.e., abstraction entitlement reduction) as well as limiting the irrigated area (Scott et al. 2014). These measures have been gradually adopted in the case of Spain, although no evaluation of its effectiveness has yet been performed. Additionally, administrative moratoriums have been implemented to avoid irrigated area expansion (e.g. the Guadalquivir and Andalusian basins), although control measures are insufficient since little surface augmentations can still be observed. Nevertheless, further ex-post evaluations are needed to understand the long-term effects of these policy actions, the changes in irrigators' behaviour and the dynamics of socioeconomic and hydrologic systems. All these factors need to be controlled in order to guarantee effectiveness of these policy measures.

Finally, it should be mentioned that a higher flexibility and a guarantee of supply, enabled the shift to higher value crops, as well as the professionalization of farmers and WUAs, among other positive outcomes. We believe that all these effects have positively contributed towards guaranteeing the welfare and income of farmers, which will lead to further gains for society, such as environmental (e.g. agricultural ecosystem services) and food security benefits, which fall outside the scope of this study.

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Conflict of Interest

None

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