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Irrigation efficiency and water-policy implications for river-basin resilience

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Abstract

Rising demand for food, fiber, and biofuels drives expanding irrigation withdrawals from surface- and groundwater. Irrigation efficiency and water savings have become watchwords in response to climate-induced hydrological variability, increasing freshwater demand for other uses including ecosystem water needs, and low economic productivity of irrigation compared to most other uses. We identify three classes of unintended consequences, presented here as paradoxes. Ever-tighter cycling of water has been shown to increase resource use, an example of the *efficiency paradox*. In the absence of effective policy to constrain irrigated-area expansion using "saved water", efficiency can aggravate scarcity, deteriorate resource quality, and impair river-basin resilience through loss of flexibility and redundancy. Water scarcity and salinity effects in the lower reaches of basins (symptomatic of the *scale paradox*) may partly be offset over the short-term through groundwater pumping or increasing surface water storage capacity. However, declining ecological flows and increasing salinity have important implications for riparian and estuarine ecosystems and for non-irrigation human uses of water including urban supply and energy generation, examples of the *sectoral paradox*. This paper briefly examines policy frameworks in three regional contexts with broadly similar climatic and water-resource conditions – central Chile, southwestern US, and south-central Spain – where irrigation efficiency directly influences basin resilience. The comparison leads to more generic insights on water policy in relation to irrigation efficiency and emerging or overdue needs for environmental protection.

1 Introduction

Irrigation in river basins has been widely examined from a range of perspectives including crop water productivity (Molden et al., 2010), water conservation (Perry, 2011; Santos Pereira et al., 2012), and socio-economic development (Molle and Wester, 2009). Undoubtedly, irrigation expansion has led to major gains in agricultural production and food security (Falkenmark and Lannerstad, 2005), crop diversification, and profitability. As the highest-volume use of water for human purposes globally, irrigation has profound implications for other uses (urban and industrial supply, hydropower, and thermoelectric generation) especially under the dual processes of human-induced water scarcity and climate change and variability. To buffer against scarce and variable surface water flows, societies appropriate basin water resources using storage reservoirs, groundwater pumps, and reuse schemes that capture excess diversions (urban wastewater and irrigation return flows). The result is that riparian ecosystems are experiencing direct, often irreversible, impacts of water appropriation. As basins around the world continue infrastructure expansion based on full surface diversion and groundwater depletion, instream flows cross critical thresholds leading to intermittency, loss of ecosystem services, and regime-shifts as natural riparian systems become social-hydraulic systems. In the latter, intensive water management seeks to allocate water saved through efficiency to enhance multiple uses of water and increase water productivity. Less frequently do policies effectively constrain or limit agricultural expansion using saved water, as evaluated below. Thus, irrigation efficiency is of emblematic concern to resource use and management in Anthropocene – the subject of the present HESS special issue. This paper examines the assumptions, mechanisms, contradictions, and conditions required for water savings through irrigation efficiency. Three cases from central Chile, southwestern US, and south-central Spain are compared with illustrative examples and lessons learned for a broader set of conditions in irrigation-intensive, heavily appropriated river basins worldwide.

We take as our point of conceptual departure the policy implications of irrigation efficiency raised by Lankford (2012), who builds on the work of numerous others, many of whom we cite in this paper. Of particular concern is whether and under which conditions “basin allocation irrigation efficiency” drives water depletion and attendant water quality deterioration. Under purely surface-water diversion systems of irrigation used principally by livelihood-dependent smallholders, Lankford’s “socialised localised irrigation efficiency” linking upstream and downstream users along a canal provides explanatory insight on return-flow recovery. Two conditions, however, change the within-basin configurations of water use, recovery of "lost water", and upstream-downstream positionality. First, *technology* alters the classical return-flow cycle in river basins, e.g., pumping of groundwater and lift irrigation from gravity canals. Indeed, because of inter-basin transfers, pumping increasingly challenges the basin paradigm. Additionally, pressurized irrigation alters water appropriation, and importantly, profit-motives behind investments in efficiency based on the rationale of localized capture of "saved water" that is an important driver of area expansion leading to depletion. Second, *institutions* provide backing for (or inhibit) irrigation expansion or agriculture-urban water transfers. Water rights represent an important category of institutional arrangements; in the basins we examine here, prevailing systems of rights extend ownership over "saved water" and thereby justify technology investments.

2 Key concepts

Integrated river basin management and multiple-use systems that link uses and users of water within the river-basin spatial domain, accounting for third-party effects, are tested approaches with significant backing in concept and practice. There is growing recognition of the inter-relation between irrigation and non-agricultural uses of water with impacts, scarcity, and water-quality degradation occurring across sectors, e.g., cities influence agriculture through priority appropriation and wastewater flows while irrigation and food security may provide the public rationale to invest in infrastructure that in turn impacts cities and ecosystems.

Molle and Wester (2009) describe the evolution of such inter-relations as river basin trajectories, in which large hydraulic infrastructure projects are commonly superseded by local, often-private investment in efficiency improvements. The conditions that help explain this transition are closely linked to technology and institutions, as outlined above.

2.1 River basin resilience

Flexibility, capacity, and redundancy are features of ecological resilience that, when applied to river-basin systems, provide explanatory insight on recovery from crises such as extended drought (Scott and Buechler, 2013; Rockström, 2003). Specifically for irrigation, groundwater “incidental” recharge from inefficient canals (Foster and Perry, 2010) is an important source of water that may indeed have higher value in economic, management, and buffering terms than the primary surface water source. Such capacity may be degraded in the basin trajectory currently underway in many “closed” (fully developed, over-allocated) river basins where management is centered on recapture of “losses” through efficiency. Resilience can be enhanced through adaptive management to maintain or expand flexibility while preserving redundancy (Scott et al., 2013). This is akin to redundancy, or “lacunae” (Ulanowicz et al., 2009), in ecological terms.

In river basins, upstream-downstream positionality matters, i.e., as we will show, the Limarí basin in Chile is different from Imperial Valley (next to Salton Sea, a “salt sink”). Furthermore, transfers of multiple types we consider – rural–urban and above–below canal – actually reconfigure basins. These dynamics also alter which users or ecosystems are able to retain flexibility and which ones experience the impacts of efficiency-driven scarcity and quality degradation.

2.2 Irrigation efficiency tradeoffs

This paper seeks to address the underlying question: *are tradeoffs inevitable in water conservation through irrigation-efficiency interventions, ecosystem services, and agricultural production?* Water scarcity, irrigation (in-)efficiency, losses/savings, and water productivity in physical and economic terms have been extensively characterized (Molden et al., 2010; Perry, 2011; Falkenmark and Lannerstad, 2005). Our conceptual approach (see Fig. 1) draws from the definitions posed by Perry (2011, p. 1841). In irrigation, the consumed fraction (evaporation and transpiration) comprises beneficial consumption (e.g., water transpired by an irrigated crop) and non-beneficial consumption (water transpired by weeds or evaporated from waterlogged land). Additionally, the non-consumed fraction comprises a recoverable fraction (return flows serving as downstream irrigation sources or aquifer recharge) and a non-recoverable fraction (flows to a saline sink such as the sea). Perry (2011) and Whittlesey (2003) identified the potential consequences of irrigation improvement resulting in reduced water availability elsewhere or over time. We will build on this through case examples below.

Agronomists define irrigation efficiency as fraction of the water applied that is stored in the soil and becomes available to satisfy crop water requirements (beneficial use). Irrigation is then planned (frequency and operation time) considering available water content in the soil, crop evapotranspiration and systems efficiency. Management practices such as the use of variable flows for furrow irrigation, operation of the system during hours of low atmospheric water demand, and field leveling can substantially increase irrigation efficiency and produce positive effects on crop productivity. However, systems efficiency is somewhat bounded and further improvements in efficiency are achieved only through technological change.

Structural changes in efficiency require an investment in technology that is not always possible due to financial constraints, especially in small-scale agriculture. In addition we observe that in places where the price of water is low or null (relative abundance) there are little incentives to invest in efficiency improvements. Therefore we usually find low efficiency systems (such as flood irrigation) in places where there is unrestricted water supply and/or frequently associated with low value crops.

The focus on water stored per water applied has prevented farmers from looking at other measures of efficiency, which could be of beneficial use under water-limited conditions. Water use efficiency (a concept often used in eco-physiology) measures it as productivity per unit water transpired. A related measure like crop yield per unit water applied could be adopted for management practices to make strategic decisions (such as water allocation) and also be of help to analyze the impact of controlled deficit irrigation.

3 Case examples

We explore the tradeoffs among irrigation, efficiency, ecosystem services, and agricultural production with reference to river-basin resilience for the Limarí Basin in Chile, the Imperial Valley in the US, and the Guadiana Basin in Spain (see Fig. 2).

3.1 Limarí Basin

The Limarí Basin is located in semi-arid central Chile with an average precipitation of slightly over 100 mm heavily concentrated in winter months as is predominant in the Mediterranean climate that dominates this region in Chile (see Table 1).

The Limarí Basin is actively undergoing the twin processes of hydroclimatic change and irrigation expansion primarily through pumped lift above the contour canals, a process driven by the economic advantages of high-value crop production under a system of reservoirs and favorable climatic conditions. Before this system of reservoirs was completed in the late 1970s irrigated land in the valley floor amounted to roughly 40 000 ha. According to the last Agriculture census that figure has increased in 30 yr to more than 60 000 ha. Irrigation efficiency on the other hand has moved from a system dominated by flood irrigation to more than 60 % covered by high efficiency drip irrigation technology (see Table 1).

The prevailing water rights system gives complete ownership to water independent of land ownership and final use of water (Bauer, 2004) and thus fosters irrigation efficiency in exchange for benefits that could be capitalized in terms of increased acreage or water transactions. This economic driver translates in a scenario today where high value species like vineyards and orchards dominate a crop mix previously abundant on low value crops such as cereals (see Table 1). This change in crop mix has been enhanced by subsidies given by the public sector through regulations designed to promote the development of high irrigation efficiency and irrigation security. The extended irrigated acreage that has resulted from this mix of water and irrigation policies should come as no surprise considering that the subsidy is granted to applicants who can demonstrate that there will be an extension of irrigated land with the aid of improved irrigation efficiency (Ley No. 18.450 de Fomento al Riego).

The extension in irrigated land, especially with permanent crops, has reduced the ability in the basin to withstand sustained drought episodes as the one the basin is confronted at the time of preparation of this paper. This loss in adaptive capacity could affect the long-term sustainability of agriculture in this basin considering droughts should become more prominent according to climate change projections (Vicuña et al., 2011, 2012).

The result of high total use of value reflects also on very little amount of water flowing at the outlet of the basin as can be seen in Fig. 3, which compares monthly streamflow before the basin reaches the ocean with monthly precipitation at the valley floor. The figure shows that only during periods of significant precipitation (e.g., 1997 and 2002) does monthly streamflow exceed $5\,\mathrm{m^3\,s^{-1}}$. It is important to note that the recorded information does not allow us to infer the situation prior to the improvements in irrigated acreage and irrigation efficiency but we can conjecture that streamflow was higher and less variable earlier in the history of the basin.

3.2 Imperial Valley

Hydrologically part of the New River basin, the extreme aridity (71 mm annual precipitation) of the Imperial Valley in California means that surface water is essentially all irrigation (and return flows) that come via conveyance canal from the Colorado River basin. By contrast with the Limarí case, increased efficiency in the Imperial Valley has been pursued largely with the objective of transferring water out of the basin for urban uses (IID, 2007), with a resulting decline in local resilience including reductions in aquifer recharge resulting from seepage across the US–Mexico border (Maganda, 2005). Securing water for environmental conservation in the binational region is complicated by high urban demand, rising water prices, and salinity constraints on wastewater and irrigation return flows (Medellín-Azuara et al., 2008).

A cornerstone of pursuing irrigation efficiency improvements in Imperial Valley and the lining of the All American Canal has been to transfer “saved” water to urban uses in San Diego – outside the Imperial Valley basin. In the 1990s San Diego had experienced dramatic reductions in alternative sources of supply from the Metropolitan Water District resulting from drought conditions. In 2003 the Imperial Irrigation District (IID) signed the Quantification Settlement Agreement (QSA) to initiate phased water transfers to San Diego and Coachella Valley. As shown in Fig. 4, by 2026 this would be increased to 303 000 acre-feet (374 Mm^3) annually, of which 130 000 acre-feet (160 Mm^3) had to come from on-farm efficiency improvements. IID (2007) estimated that canal lining represented the lowest-cost method of water conservation (13–15 US$ acre-foot^{-1}, equivalent to 10 500–12 200 US$ Mm^{-3}). On-farm water conservation to be achieved through voluntary adoption of sprinkler irrigation and other efficiency improvements would be the most expensive, in excess of the 300 US$ acre-foot^{-1} (243 200 US$ Mm^{-3}) “target” cost set for the transfer arrangement in the QSA. Additionally, automated monitoring and control systems costing approximately 160 US$ acre-foot^{-1} (129 700 US$ Mm^{-3}) were identified to have potential to save in excess of half a million acre-feet (almost 700 000 Mm^3) of canal spillage and tailwater discharges, which ultimately flow to the Salton Sea. The price structure was subsequently renegotiated in 2009 with the result that IID forecast its 2016 annual revenues to be in excess of 62 million US$ based on an agreed transfer of 100 000 acre-feet at 624 US$ acre-foot^{-1} (IID, 2009). However, several of the QSA provisions passing certain environmental mitigation costs to California taxpayers were challenged in court.

It should be noted that the Salton Sea is below sea level and was created in 1905 by the accidental rupturing of Imperial Valley irrigation canals. It covers an average of 1360 km^2 and receives inflow of 1.36 million acre-feet (1.68 km^3), which is declining as a result of irrigation efficiency and water transfers coupled with climate change. Salinity levels, already 25 % greater than that of the Pacific Ocean, are increasing with the result that only tilapia fish are expected to survive. The Salton Sea is an important resting stop for birds on the Pacific flyway, with over 400 species documented.

3.3 Guadiana Basin

The Guadiana River Basin (67 147 km^2) is a large trans-national basin shared by Spain (83 %) and Portugal (17 %). The analysis presented here refers to the Spanish portion only, with data from Ciudad Real and Badajoz municipalities representing 75 % of the total area. The basin has a predominantly continental Mediterranean climate with annual average precipitation of 521 mm yr^{-1} being greatly exceeded by annual average potential evapotranspiration of 983 mm yr^{-1}. The mean annual temperature is 16 °C. The variability of the hydrologic regime causes frequent and severe droughts leading to significant social, economic, and environmental impacts. The existence of important groundwater reserves, mostly concentrated in the upper part of the basin, as well as the presence of large reservoirs in the middle and lower sections of the basin (with storage capacity exceeding 9000 Mm^3, more than twice the mean annual flow) has helped to increase resilience and to reduce vulnerability to drought. At present, total water withdrawals (2356 Mm^3) account for 48 % of the total renewable resources (CHG 2013), showing evidence of severe water stress.

Agriculture accounts for 90 % of all water consumption, compared to 7 % for domestic use and 3 % for industry. Irrigation covering 400 000 ha provides employment in rural areas, contributes 50 % of total value added in agriculture, and serves as the base for many agribusinesses (CHG, 2013). Irrigation development in the region started in the early 1960s and 1970s with the creation of reservoirs and distribution network infrastructure, and in response to technological advances including new irrigation and well-drilling techniques – although with scarce planning and control on the part of the water administration (Varela-Ortega et al., 2011; Blanco-Gutiérrez et al., 2013), as well as economic incentives linked to the European Common Agricultural Policy (CAP), which Spain adopted in 1986 (Varela-Ortega, 2011). As seen in Fig. 5, in the last forty years, the area in irrigation had expanded by 300 % (from 140 730 ha in 1970 to 400 431 ha in 2010).

During the 1980s and 1990s, traditional irrigation was gradually displaced by intensive irrigation, in part encouraged by the establishment of direct payments based on crop production from the CAP, which favored the expansion of high-yielding water-intensive cereals, e.g., maize, rice, barley, and wheat. The 2003 CAP reform (EC, 2003) decoupled many subsidies from production, which diminished the comparative advantage of subsidized irrigated crops and resulted in continued reductions in land use for cereal farming. High value crops with low water requirements and a high impact in labor such as vineyards, olives trees, fruit trees (peach, plum, pear), and vegetables (tomato, melon) are the current trend.

Irrigation has been a key driver for socio-economic development in the region. It has increased agricultural production and crop diversification, enhancing income generation, favoring labor creation, and promoting settlement of the rural population. However, irrigation development has been achieved at the expense of negative environmental impacts, namely alteration of natural hydraulic river regimes, reduction of in-stream flow volumes, disappearance of riparian vegetation, over-pumping of fragile aquifers, and drying up of springs and wetlands (e.g., Tablas de Daimiel National Park, a UNESCO Biosphere Reserve, and a groundwater-dependent Ramsar wetland) (Blanco-Gutiérrez et al., 2011). In 1987, La Mancha Occidental and Campo de Montiel aquifers, the largest and most important in the basin, were legally declared overexploited with strict regulatory measures applied to both public and private water users. All water resources in Spain are public goods since 1986, when the Spanish Water Act 29/1985 made groundwater ownership public. In addition to surface water users, groundwater users were granted administrative concessions of water use rights defined by specific water allotments. Yet, those who wished to remain in the private property regime were allowed to do so. Therefore, public and private regimes still coexist.

In 1991, drilling new wells or deepening the existing ones was prohibited and entitled water assignments were cut by half in accordance with stringent pumping regimes (Varela-Ortega et al., 2011). This situation encouraged irrigators to adopt modern water saving technologies and to replace traditional surface irrigation methods with lowvolume irrigation techniques. In 2000, 75 % of the irrigated land (almost 250 000 ha) was under pressurized irrigation systems, with center pivots being the most extensive (see Fig. 6).

Irrigation modernization accelerated in the 2000s through the implementation of an ambitious nation-wide irrigation modernization program, the Spanish National Irrigation Plan (2002–2008), which was revitalized with a second plan, the Emergency Plan for the Modernization of Irrigation (2006–2008) after the extreme drought of 2004–2005. Modernization was based on the improvement of storage facilities, lining and piping of old canals, and on the development of new irrigation and drainage systems, including the adoption of on-farm modern irrigation technologies. In total, 600 million € were invested in the Guadiana region, and notably in the middle part of the basin, where 185 000 ha (about 45 % of the total irrigated land) were completely refurbished. Farmers directly pay for a third of the investment costs with 50 yr amortization. These irrigation modernization programs contributed to achieve the stated policy objectives of guaranteeing water demand to irrigators to reduce the impact of climate variability, raising the productivity of water use, i.e., obtaining a higher yield of production per unit of water used, and improving farm competitiveness and crop diversification (Varela-Ortega, 2011). However, the resulting water savings obtained from increasing technical efficiency have not been translated into reduced water withdrawals, in similar fashion to elsewhere in Spain and other parts the world (Fuentes, 2011; Lecina et al., 2010; López-Gunn et al., 2012; Ward and Pulido, 2008). According to AEVAL (2010), water savings in the Guadiana basin were 243 Mm^3 yr^{-1} from 2002 to 2006 and 94 Mm^3 yr^{-1} from 2006 to 2008. This study underlines that whereas water abstractions for irrigation have remained broadly constant, water allotment rights have not changed in the last ten years (7500 m^3 ha^{-1} for surface irrigators, and 4200 m^3 ha^{-1} for groundwater irrigators except for those located in overexploited aquifers who are limited to 2000 m^3 ha^{-1}). Instead, water savings have been re-used to expand the irrigated area and to support a higher value and more diversified agricultural production, offsetting the intended impact of water saving irrigation technologies.

4 Conclusions

Irrigation improvements can present unintended consequences when broader scales and multiple uses of water are considered. In a process we term the *efficiency paradox*, water "saved" leads to increased use of water through irrigation expansion, as shown in the Limarí and Guadiana cases. In a related but distinct process we term the *scale paradox*, water "loss" upstream serves as supply downstream particularly for ecosystems, as observed by Perry (2011) and shown here for the Imperial Valley – Salton Sea and Guadiana – Tablas de Daimiel National Park cases. The scale paradox may also apply to downstream irrigators, as evidenced in the reduction of cross-border seepage flows to Mexico resulting from the lining of the All American Canal. A third process involves the *sectoral paradox*, in which savings are reallocated to alternative uses, e.g., water transferred from Imperial Valley to San Diego city.

Of broader relevance beyond the specific cases considered in this paper, irrigation efficiency without caps on use – or limits to area expansion – may increase production (and productivity) but it widens the "resilience gap" under conditions of water scarcity. Eliminating slack in the system through stringent water conservation and allocation of savings to new uses can resulting in the "hardening" of demand that will entail crop loss or irrigated area restrictions under future conditions of water shortage. This is particularly true for the integrated management of water and land to meet ecological flow requirements under changing climate scenarios. Thus, a basin's capacity to meet human and ecosystem water needs often follows a moving target.

Policy mechanisms to reserve surplus water in the dam or aquifer instead of expanding irrigation include regulated controls on irrigated area, price incentives, and provision of information to support farmer and irrigation district decision-making to better adapt to future contingencies. The latter represents a case of "socialised localised irrigation efficiency" (Lankford, 2012). Investing public resources to anticipate and offset the effects of water scarcity ex-ante represents a more effective adaptive response to drought than ex-post mitigation efforts.

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Table 1. Basin comparative indicators.

	Annual precipitation (mm)	Winter precipitation (mm)	Average temperature (˚C)	Total area (km^2)	Evolution of area under irrigation (ha) 1975	Evolution of area under irrigation (ha) 2007	Irrigation method (% area) 1975	Irrigation method (% area) 2007
Guadiana Basin (portion in Spain)	521	241	15	55 527	140 730	400 431	Flood (98 %)	Flood (17 %), Sprinkler (32 %), Drip (51 %)
Imperial Valley[a]	71	43	23	11 608	183 248	151 829	Furrow (94 %)	Furrow/border (85 %), Sprinkler (15 %)
Limari Basin[b]	109	96	17	12 000	38 000	64 000	Flood (100 %)	Flood (40 %), Drip (60 %)

	Evolution of crop mix							
	1975				2007			
	Cereals	Vegetables	Orchards (vineyards)	Pasture and Other	Cereals	Vegetables	Orchards (vineyards)	Pasture and Other
Guadiana Basin	43 %	23 %	3 %	31 %	38 %	13 %	25 %	25 %
Imperial Valley[a]	30 %	16 %	1 %	53 %	11 %	28 %	2 %	59 %
Limari Basin[b]	51 %	18 %	17 %	14 %	3 %	8 %	48 %	40 %

[a] 1974 and 2007 Census, respectively.

[b] 1975 from Paloma Reservoir design; 2007 from Agriculture-Livestock Census.

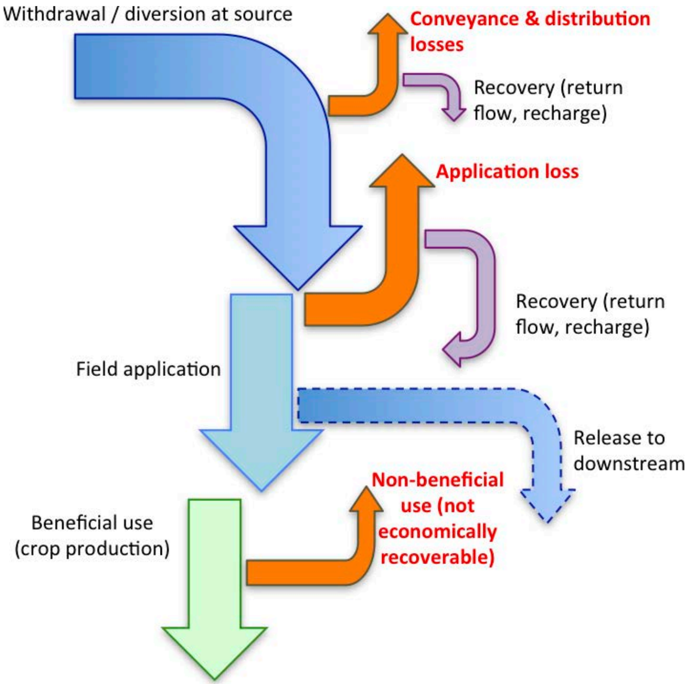

Fig. 1. Irrigation efficiency, loss/depletion, and recovery.

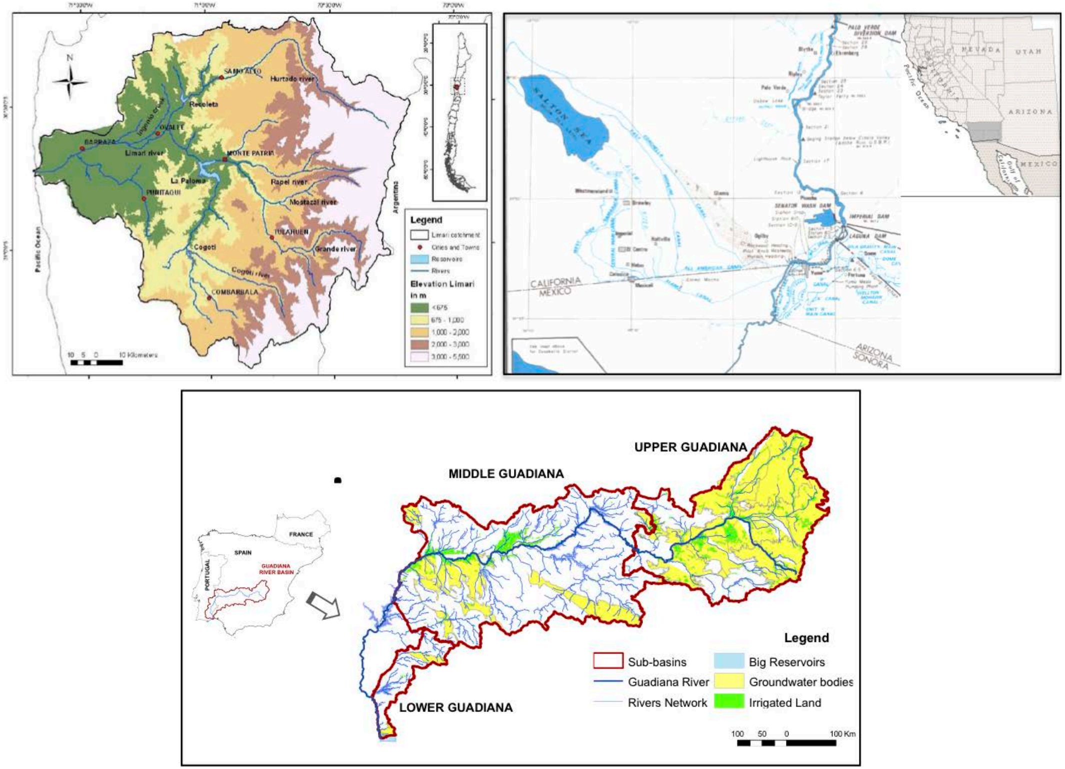

Fig. 2. Basin locator maps.

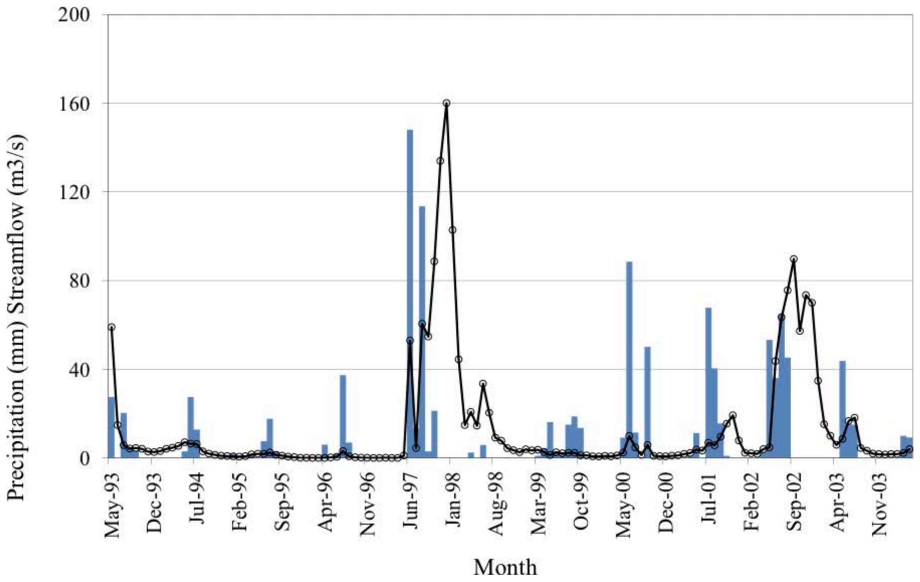

Fig. 3. Limarí Basin – comparison of monthly streamflow (Panamerican gauge station) and precipitation (Ovalle station).

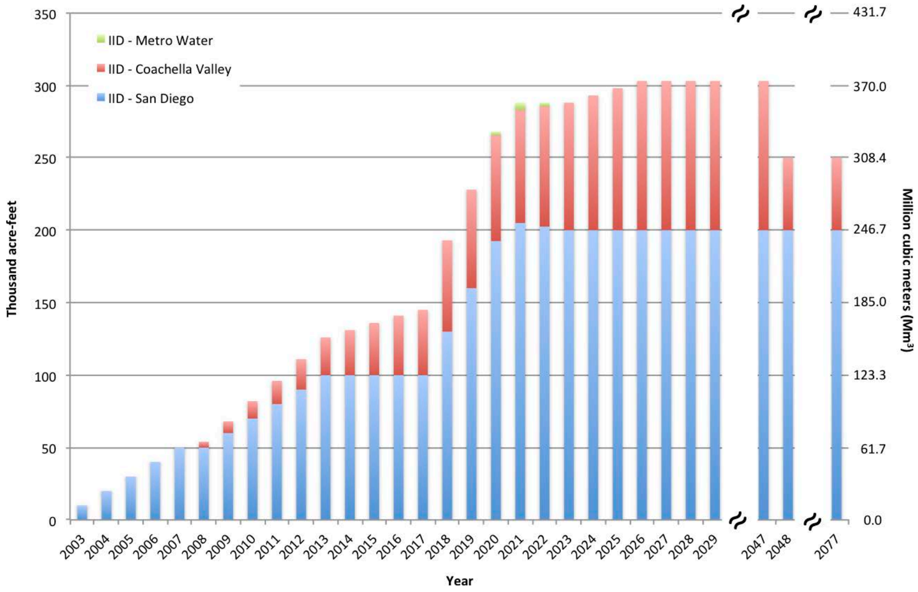

Fig. 4. Phased transfer of water from Imperial Irrigation District to urban uses, 2003–2077. Source: QSA (2003), http://www.sdcwa.org/sites/default/files/files/QSA_final.pdf.

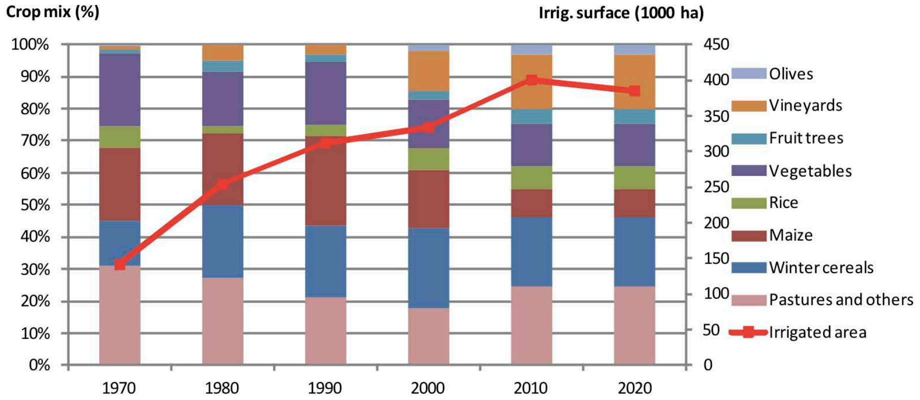

Fig. 5. Increase of irrigated area and change in crop mix in the Guadiana basin, 1970 to 2020. Source: Based on statistical data from CHG (2013) and MAGRAMA (2013).

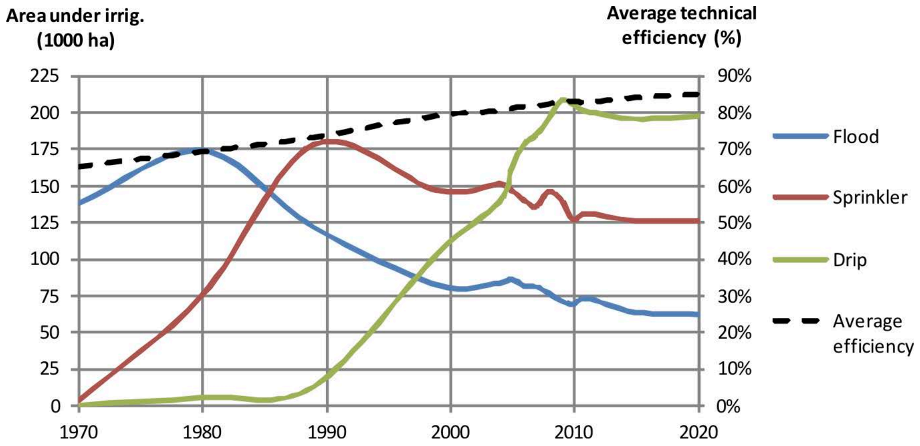

Fig. 6. Change in on-farm irrigation methods and estimated water use efficiency in the Guadiana Basin, 1970 to 2020. Source: Based on statistical data from CHG (2013), INE (2009), and MAGRAMA (2012).