



Improving water-efficient irrigation: Prospects and difficulties of innovative practices

Les Levidow^{a,*}, Daniele Zaccaria^b, Rodrigo Maia^c, Eduardo Vivas^c, Mladen Todorovic^d, Alessandra Scardigno^d

^a Development Policy and Practice, Open University, UK, Milton Keynes MK7 6AA, UK

^b University of California, Davis, CA, United States

^c Universidade do Porto, Praça de Gomes Teixeira, Portugal

^d CIHEAM—Mediterranean Agronomic Institute of Bari (IAMB), Bari, Italy

ARTICLE INFO

Article history:

Received 9 February 2014

Accepted 17 July 2014

Keywords:

Innovative irrigation practices

Water-efficiency

Water users organisations

Shared responsibility

Knowledge-exchange system

ABSTRACT

Innovative irrigation practices can enhance water efficiency, gaining an economic advantage while also reducing environmental burdens. In some cases the necessary knowledge has been provided by extension services, helping farmers to adapt and implement viable solutions, thus gaining more benefits from irrigation technology. Often investment in technological improvements has incurred higher water prices, however, without gaining the full potential benefits through water efficiency. Farmers generally lack adequate means and incentives to know crops' water use, actual irrigation applications, crops' yield response to different water management practices, and thus current on-farm water-efficiency levels.

Those general difficulties are illustrated by our two case studies investigating options, stimuli and difficulties to improve water-efficient practices. The two areas have strong stimuli for improvement but lack a knowledge-exchange system to help farmers and resource managers identify scope for improvements. Partly for this reason, farmers' responsibility for efficient water management has been displaced to hypothetical prospects, e.g. extra supplies from reuse of treated wastewater or a long-term low water pricing. In both cases a displaced responsibility complements the default assumption that farmers' irrigation practices already have adequate water-use efficiency. Under current circumstances, agricultural water management will maintain the unknown water-efficiency level and farmers will have weaker incentives to make efforts for more efficient practices. A continuous knowledge-exchange is necessary so that all relevant stakeholders can share greater responsibility across the entire water-supply chain. On this basis, more water-efficient management could combine wider environmental benefits with economic advantage for farmers.

© 2014 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/3.0/>).

1. Introduction

Irrigation systems have been under pressure to produce more with lower supplies of water. Various innovative practices can gain an economic advantage while also reducing environmental burdens such as water abstraction, energy use, pollutants, etc. (Faurès and Svendsen, 2007). Farmers can better use technological systems already installed, adopt extra technologies, enhance their skills in soil and water management, tailor cropping patterns to lower water demand and usage, reduce agrochemical inputs, etc.

Water-efficient practices potentially enhance the economic viability and environmental sustainability of irrigated agriculture, without necessarily reducing water usage. To inform such practices, experts have developed various models of water efficiency, yet these are little used by farmers.

Through two case studies in the EU context, this paper will address the following questions:

- When an irrigation area invests in innovative technology, how can its operation help farmers to achieve the full potential benefits together, e.g. an economic advantage, greater water-use efficiency and lower resource burdens?
- Why are innovative technologies often applied in ways which miss the full potential benefits?

* Corresponding author. Tel.: +44 20 7482 0266.

E-mail addresses: LLevidow@open.ac.uk (L. Levidow), dzaccaria@ucdavis.edu (D. Zaccaria), rmaia@fe.up.pt (R. Maia), evivas@fe.up.pt (E. Vivas), mladen@iamb.it (M. Todorovic), scardigno@iamb.it (A. Scardigno).

- What tensions arise among various objectives and potential benefits?
- How can these difficulties be addressed?

The paper first surveys analytical perspectives on irrigation efficiency – especially the means, incentives and limitations – as a basis to analyse two cases and draw general conclusions.

2. Innovative irrigation practices: Analytical perspectives

Innovative irrigation technology is generally promoted as raising water-use efficiency along with multiple benefits, but these remain elusive in practice, as outlined in the first sub-section below. The limitations have fundamental reasons, as outlined in Section 2.2. To address these issues, our case studies are introduced in Section 2.3.

2.1. Practical limitations of water-efficient irrigation technology

EU policy frameworks place great expectations upon technologies to improve water efficiency. The European Commission emphasises ‘technological innovation in the field of water, given that water efficiency will be an increasingly important factor for competitiveness’ (CEC, 2008). According to the European Parliament, solutions should be found in ‘clean technologies that facilitate the efficient use of water’ (EP, 2008).

Such technological expectations arise in expert reports on agricultural water use:

Water-efficient irrigation, irrigation on demand and irrigation using brackish water are technologies that will enable the better husbandry of more scarce freshwater resources. Technological developments in respect of irrigation will encompass sensors and communication, intelligent watering systems and high-efficiency delivery mechanisms for water and nutrients, as well as the means of incorporating all of these elements into irrigation ‘packages’ (EIO, 2011: 25).

Likewise water efficiency can be enhanced by better using current installations and/or by adopting new equipment (WssTP, 2012: 9).

The main European farmers’ organisation has likewise advocated technological means to increase water efficiency. In particular this needs ‘investments in more efficient irrigation systems, use of new technologies (e.g. soil moisture and canopy sensors) to better match irrigation with plant needs, and good agricultural practices’, such as conservation tillage, management of soil fertility and water retention capacity, and scheduling of irrigation during night to reduce evaporation (COPA-COGECA, 2007: 4). The basis for improvement is described as follows:

... water efficiency measures that provide complementary benefits, such as reduced energy needs or other environmental benefits, will also deliver better results. In many Member States, efforts are being made to increase the water storage capacity of soil under agricultural land use. The modernisation of irrigation systems has steadily progressed and water productivity has also improved considerably (COPA-COGECA, 2013: 3)

As indicated above, greater water-use efficiency depends on better agricultural practices alongside extra technology. Yet companies generally promote irrigation technology as if it inherently brings all the benefits (interview, COPA-COGECA, 08.07.13). Improperly managed ‘hi-tech’ systems can be as wasteful and unproductive as poorly managed traditional systems (Perry et al., 2009). When incorrectly applied, irrigation technology ‘can cause losses arising on investments made by farmers, thus decreasing the

economic water productivity index and the overall sustainability’ (Battilani, 2012).

Beyond a problem-diagnosis of inefficiency, moreover, intensive farming practices can degrade soil and water resources, especially through more input-intensive farming in crops such as maize, vegetables, orchard and vine cultivation:

Intensive arable production is partly responsible for poor soil structure, soil erosion, loss of soil OM [organic matter] and pollution from fertilisers and pesticides. ... The expansion of maize cropping and the move to growing winter cereals in particular have contributed to soil erosion even further (Miller, 2007: 44–45).

Such harmful practices have been driven and supported by EU policies. In past decades CAP subsidies have tended to favour crops with high water demands, such as maize, thus increasing the risk of water shortages under climate-uncertain conditions (García-Vila and Fereres, 2012). Either as price-support or area-based, CAP subsidies likewise have ensured the profitability of some water-intensive crops such as cotton which otherwise would be phased out under a market-orientated scenario; likewise water-price subsidies.

In some cases, water-price increases have induced farmers to adopt technology and appropriate practices for conserving water (Caswell and Zilberman, 1985). Yet water-pricing policies often have been ineffective means to reduce water demand (Molle and Berkoff, 2007; Molle, 2008). Farmers experience rising water prices as an extra penalty. Rather than higher water prices, administrative water allocation or re-allocation lowering the supply often has led farmers to adopt water-efficiency practices (Molden et al., 2010). If agricultural water demand is inelastic, then policies which encourage changes in cropping patterns can be more effective than higher prices (Fraiture and Perry, 2007; Iglesias and Blanco, 2008; Kampas, 2012).

Inelastic water demand results from farmers’ perspectives on water benefits. Water-use efficiency (WUE) and water productivity (WP) are often used interchangeably but have different meanings. WUE specifically means the ratio of biomass produced per unit of irrigation water used, i.e. the sum of transpiration by the crop and evaporation from the soil (Sinclair et al., 1984). By contrast, WP means the ratio of above-ground biomass per unit of water transpired by the crop (Steduto, 2007). Both terms have relevance to farmers’ economic goals. WUE interests mainly the water districts or management agencies, while WP interests more farmers and research community. WP better speaks to perspectives linking water usage with production levels and economic benefit (interview, COPA-COGECA, 08.07.13).

Yet even WP remains distant from farmers’ perspectives. They generally perceive ‘irrigation efficiency’ as maximising net revenue rather than saving water (Knox et al., 2012). Policies seek to lower water usage, and river basin managers try to allocate limited supplies, yet water-saving is not a priority for most farmers (Luquet et al., 2005). They manage labour and other inputs to get better economic gains (Molden et al., 2010). Towards that economic aim, most growers make irrigation decisions by relying on subjective judgements, based only on their practical experience and observation (Knox et al., 2012). Consequently, there have been limited benefits from irrigation technology, as well documented in the technical literature; the following examples compare various techniques.

For example, mobile-laboratory evaluations compared the distribution uniformity and irrigation efficiency of various irrigation systems in California. Although microirrigation systems are seen as ‘efficient technologies’, they were performing less well than traditional surface irrigation methods such as furrows and borders. To gain the extra benefits of such technology, most important is

adequate system design, alongside proper installation, operation and maintenance, regardless of the irrigation method used (Hanson et al., 1995).

Howell (2003) and Irmak et al. (2011) reported the attainable application efficiencies for different irrigation methods, assuming irrigations are applied to meet the crops' water needs. Microirrigation has the potential to achieve the highest uniformity (90%) in water applied to each plant, yet poor uniformity and application efficiency can result from various causes, e.g., inadequate maintenance, low inlet pressure or pressure fluctuations, emitter clogging and inadequate system design (Hsiao et al., 2007). Consequently, microirrigation technology has on-farm efficiencies varying from 0.7 to 0.95 (Howell, 2003).

As another example, a Spanish study compared various irrigation methods via the annual relative irrigation supply index (ARIS), i.e. a ratio of water applied versus water required. It found a greater efficiency of solid-set and drip than surface irrigation. But average annual figures conceal great variations in water applied to a given crop and irrigation efficiency at farm level, partly for lack of adequate knowledge. A remedy would be 'actions to improve farmers' water management via a combination of irrigation advisory services and policy measures' (Salvador et al., 2011: 586).

2.2. Reasons for those limitations and ways to overcome them

Given the above water-efficiency limitations in applying irrigation technology, the literature has outlined some fundamental reasons. They include the following: irrigation equipment is promoted as if the technology per se brings various benefits, farmers seek to maximise net income rather than water productivity per se, innovative technologies can achieve the full potential benefits only through appropriate technical advice, and farmers lack a knowledge-system for anticipating effects of specific irrigation practices or for retrospectively evaluating their irrigation efficiency.

Although research has developed technical scheduling procedures to improve agricultural water management, these have been little adopted, for many reasons.

The one most frequently mentioned by growers is the lack of perceived [financial] benefits relative to their current practices, which they consider adequate. Ease of use and the expenses involved are also important grower considerations (FAO, 2012).

Technical advice on irrigation scheduling is little used at farm level; at most, it helps retrospectively to evaluate seasonal approaches (ibid.).

One obstacle is inadequate knowledge about proper irrigation levels and scheduling over a growing season. Farmers generally lack adequate assistance to develop and adopt better approaches for environmental sustainability, while also maintaining their financial and social objectives (Pereira et al., 2012: 39). For example, sub-surface moisture sensors can improve knowledge about a crop's need for water. But the technology has limitations, so farmers need technical advice to interpret the measurements; for example, 'soil humidity sensors are still neither easy to handle nor reliable' (WssTP, 2012: 33). Moreover, these sensors are not well adapted to all soil types; their installation and maintenance requires the employment of specialised technical staff. The same is true for the canopy sensors, whose proper application is limited to some crops and during specific growing stages, periods of day and climatic conditions.

Improvements in irrigation practices depend on quantitative knowledge of farmers' current practices in relation to actual and potential crop water use:

Any effort to improve water use efficiency needs to start with the assessment of the actual and attainable efficiencies for the given situation, as quantitatively as possible. This information is fundamental for making rational improvements aiming at raising the overall efficiency to the attainable level (Hsiao et al., 2007: 228, 218).

But such information is rarely available to farmers.

Such difficulties arise for water-management improvements through expert systems. Decision Support Systems (DSS) have aimed to improve crop water use efficiency at farm and water basin scale, but few are widely applied, given the necessary specialised skills. For a DSS to be successful, the key elements have been: giving farmers a simple, timely, user friendly, free-of-charge, informative system helpful to decide how much to irrigate in everyday practice; tailoring the tools for a large number of crops; calculating the irrigation profitability; and assessing the economic benefit, especially its relevance to the next irrigation. Such benefits have been demonstrated by the Irrinet project in Italy's Emilia Romagna (Battilani, 2012). Thus more reliable information systems and expert capacity are necessary to guide farmers in using water more efficiently (Battilani, 2013). This exemplifies the broader need for farmer training and education in order to improve modern irrigation management.

As a way forward in the UK, expert support has been recently linking farmers' responsibility, economic benefits and practical knowledge. A 'pathway to efficiency' improves the irrigation network, alongside better practices of soil and water management, e.g. by monitoring whether the right amounts are used at the right place and time. 'Using financial criteria for water efficiency rather than an engineering one appears a sensible approach when assessing irrigation performance at the farm level, since any managerial (e.g. scheduling) and operational (e.g. equipment) inefficiencies associated with irrigation are implicitly included in the assessment' (Knox et al., 2012: 3). In particular, 'On-farm water auditing and benchmarking have the potential to provide useful information to farmer decision making, with respect to identifying operational and management changes to improve irrigation system performance and water productivity, and evaluating potential investments in new technology (and advanced practices) or infrastructures' (ibid: 7).

Such approaches have addressed various obstacles to water-efficiency measures. To exploit the full technological potential requires a broader dissemination of their benefits, specific training of farmers, and coupling properly-designed technological solutions with more precise operational practices to benefit farm economic performance (e.g. Tollefson and Wahab, 1994). In particular, advisory-extension services have enhanced irrigation practices which better fulfil potential benefits of irrigation technology (Hergert et al., 1994; Benham et al., 2000; Ahearn et al., 2003; Genius et al., 2014; Parker et al., 2000; Gold et al., 2013).

Beyond the farm level, greater resource efficiency also depends on shared responsibility among stakeholders, according to the World Business Council for Sustainable Development:

Business undoubtedly has many opportunities to increase its eco-efficient performance and thereby to help de-couple use of nature from overall economic growth. . . Establishing framework conditions which foster innovation and transparency and which allow sharing responsibility among stakeholders will amplify eco-efficiency for the entire economy and deliver progress toward sustainability (WBCSD, 2000: 6–7).

Analogous issues arise for service-oriented irrigation schemes, designed so that farmers can flexibly obtain water at their convenience, e.g. through on-demand delivery schedules. Here responsibility has institutional complexities. For example, a water users' organisation (WUO) bears largely fixed costs, as well as

somewhat variable energy costs from drainage, excess water application, reuse, disposal, etc. If a WUO or water district relies on gravity-fed water conveyance and delivery systems, then its costs do not vary according to water-volume delivery. In such contexts, if farmers decrease water use, then the WUO must increase water prices to recover its fixed costs. Facing higher water prices, farmers may increase groundwater pumping, thus abstracting more water from aquifers, while distancing their individual practices from any group responsibility. Paradoxically, fostering greater water-use efficiency can generate a financial, environmental and institutional problem.

Given those difficulties for water-efficient techniques, their effective adoption depends on several enabling conditions, especially a policy and institutional context aligning incentives of producers, resource managers and society. Significant synergistic effects can emerge when water-efficiency practices are combined with other agronomic practices such as maintaining soil health and fertility, controlling weeds and avoiding diseases (Molden et al., 2010).

2.3. Methods and sources: EcoWater project

The above issues and earlier questions have been explored through two case studies of service-oriented irrigation schemes within a larger EU-funded research project, EcoWater (see Acknowledgements). It develops a methodology for assessing eco-efficiency at the meso level. The latter is defined as interactions among heterogeneous actors, e.g. between water-service users and providers. As generally understood, eco-efficiency means a ratio between economic advantage and resource burdens, as a basis to evaluate past or potential changes in a system.

The project uses eco-efficiency indicators to evaluate potential innovative practices including technology adoption. The project aims to: assess various options for innovative practices within a specific system; analyse the factors influencing decisions to adopt such practices; and improve understanding of the socio-technical dynamics that influence such decisions.

In the project's two agricultural case studies, farmers and/or their organisations have already invested in water-efficient technology, going beyond state subsidy alone. The irrigation distribution systems were designed for on-demand water delivery. SCADA technology at hydrants allow farmers to abstract water on demand any time and charges them according to a volumetric tiered water pricing. Each case-study area has strong stimuli for farmers to improve water efficiency, yet the full potential benefits of the technology investment were not being realised, for reasons analysed in the next two sections.

3. Sinistra Ofanto case

Dating from the 1980s, the Sinistra Ofanto irrigation scheme is among the largest multi-cropped irrigated areas in Italy. It is located in south-eastern Foggia province within the Apulia region. Irrigation is crucial for the region's agricultural production and income, but it also generates resource burdens. Nearly 18.5% of Apulia's agricultural area is under irrigation; consequently, irrigated crops have contributed 69% of the total value of regional agricultural production, recently quantified as 3.8bn Euros (Fabiani, 2010). The entire study area is characterised by a high number of small land-holdings with intensive, market-oriented practices. The main crops are vineyards, olives, vegetables and fruit orchards (in descending order). The pedo-climatic conditions are favourable for intensive cropping, but profitable farming is strongly dependent on irrigation, due to the scant rainfall and its uneven distribution across the year.

The Sinistra Ofanto system commands an area of 40,500 ha stretching along the left side of the Ofanto River, of which 38,815 ha are irrigable lands and 28,165 ha are serviced with irrigation distribution. Designed and constructed for pressurised on-demand delivery schedule, the irrigation system is managed by a large water users' organisation (WUO), the *Consorzio per la Bonifica della Capitanata* (CBC, 1984; Altieri, 1995). The system diverts water from the Ofanto River and supplies it to growers both by gravity and lifting/pumping, ensuring a pressure head of at least 2 bar at each hydrant to enable farmers using micro-irrigation methods.

The system is already equipped with modern technologies to deliver and use water efficiently. From the diversion structure on the Ofanto River, water is conveyed to the Capacciotti reservoir through concrete-lined canals and pipe conduits, along which the flow regulation devices are downstream-controlled, thus manually or automatically adjusted through calibrated control devices enabling Supervisory Control and Data Acquisition (SCADA). The Capacciotti reservoir supplies seven concrete-lined storage and compensation reservoirs equipped with downstream-control flow regulation devices that adjust inflows and outflows to feed the district's piped distribution networks based on the downstream water demand.

PVC buried pipes comprise the open-branched distribution networks. Each sector's inlet has a control unit, equipped with flow and pressure metering-control devices. Water is supplied to farms on demand by means of multi-users' electronically-fed hydrants that control and regulate the deliveries, as well as the discharges demanded and thus flowing in the pipe distribution network. These technologies installed along the main infrastructure help keeping conveyance and distribution losses within 5–10% of the total water abstracted from the Ofanto River, as reported by the WUO's engineering staff.

Although the main water supply is surface water, during recurrent water shortages farmers pump groundwater from medium-depth (100–150 m) aquifers, especially since the late 1990s (Portoghesi et al., 2013). Furthermore, studies found qualitative degradation of groundwater resources, most likely resulting from seawater intrusion into the coastal aquifer and to deep percolation of pollutants, such as fertilisers and pesticides, from intensive farming activities. Given the urgent need to assess these processes and to avoid their adverse environmental impacts, what are the prospects for water-efficiency improvements of irrigated agriculture in the Sinistra Ofanto area?

3.1. Irrigation patterns and resource burdens

The water users organisation (WUO), *Consorzio per la Bonifica della Capitanata* (henceforth the CBC), is the main irrigation management agency. It is responsible for all the sequential steps along the agriculture water supply chain, i.e. abstraction, conveyance, storage, distribution and final water delivery to farm gates. Established in 1933 by a national law of public interest, the CBC is by statute a non-profit organisation; it bears all the costs for performing its functions, and these costs are recovered through the water tariffs paid by farmers.

The CBC enforces the principle of solidarity among the different service areas. Even though the costs for supplying irrigation water differ significantly among areas supplied by gravity and by pumping, the tariff structure does not make such a distinction. Rather, as a tool to manage water use, water fees vary according to demand: volumetric tiered water tariffs progressively increase with the seasonal cumulative volumes withdrawn by each farmer. This structure is enforced through individual water metering at the delivery points; all farm hydrants are equipped with an electro-mechanical delivery device allowing the supply of water only to authorised users and storing information of each irrigation event.

Besides simplifying the network operations, this technology proved to be very useful for accurate monitoring and control of water distribution, and for achieving better understanding of the irrigation management practices followed by farmers, especially through the possibility to retrieve and analyse historical data series (Zaccaria et al., 2013).

As an irrigation service provider, the CBC is composed of irrigation service users, i.e. farmers. In performing its daily activities, the CBC attempts to reconcile objectives which may be in conflict. Its technical and administrative choices aim to achieve high water-distribution efficiency in order to maximise the economic benefit to farmers. It aims to improve water distribution and use—at the farm level, through an effective operation of the delivery network, and at field and crop level through the technical support to growers aiming at improved water management skills (ibid). Technical support to farmers was effective in the 1980s–1990s but has declined in the last decade, due to WUO budget constraints and lower revenues from Italy's farm activities.

Irrigation water demand is driven mainly by farmers' perceptions, by the climatic conditions, and by the economic value of crop yields and production factors. Even beyond periods of water shortage, in some areas farmers pump groundwater in order to avoid the following problems: (i) the restricted-flow demand delivery-schedule that prevents the quick completion of irrigation cycles in medium-large farms, (ii) the restricted-frequency demand-delivery often imposed by the CBC during water shortage periods, (iii) the need to arrange water withdrawals with neighbour farmers supplied by the same hydrants, or (iv) the tiered water fees enforced by the CBC. Also, many farmers still perceive groundwater pumping as somewhat cheaper than water supplied by the CBC, even though the contrary was shown by economic analyses (e.g. Portoghese et al., 2013).

As a more fundamental problem, both the farmers' perception and the CBC's analyses ignore the ecological costs of groundwater degradation and remediation. The CBC accepts no responsibility for water-management practices beyond the farm gate. From the growers' standpoint, groundwater pumping aims to increase and/or stabilise the economic benefits of farming activities. Often farmers combine surface water and groundwater for various reasons such as to maximise crop yields and farm net benefit, or to minimise the seasonal water fees payable to the CBC, or to prevent yield reduction arising from high salinity in the groundwater during peak-demand periods. However, this conjunctive use of surface and groundwater is based solely on farmers' economic and technical considerations, regardless of environmental burdens such as aquifer depletion and degradation. Furthermore, fields close to the river banks are often irrigated by growers with water pumped out the river. In all these situations, return flows may result from run-off through the drainage networks, as well as from percolation through the soil profile, finally reaching the downstream reaches of the river, wetlands or the aquifer.

Farm activities generate various pressures on land and water resources, including quantitative depletion and qualitative degradation, especially biodiversity loss in farmland and in the natural environment. This harm has several sources: (i) intensive farming and tillage practices, (ii) fertilisers and pesticides application on cultivated fields, (iii) water abstraction from the Ofanto River, (iv) return flows of degraded water to downstream wetlands and aquifers, (v) over-drafting of groundwater, (vi) salinity build-up in cultivated soils, (vii) energy consumption for water pumping, and (viii) increased CO₂ emissions from the energy usage related to pumping, transport, machinery, etc.

Relative to those ecological problems, much greater impetus for innovative practices comes from recurrent scarcity of water supply and the prospect of even greater future scarcity and uncertainty. Those problems in turn result from high water-demanding

crops and from irrigation scheduling practices. Such decisions are often based solely on farmers' perceptions; their systems and practices are not monitored to assess the actual performance and efficiency achievements. No systematic technical support is available to growers for their daily or seasonal irrigation planning and scheduling.

Moreover there is detailed evidence of water-use inefficiency at farm level. According to a study of farmers' irrigation practices in a nearby irrigated area with similar features, there were often mismatches between crops' water demand and irrigation applications on several occasions during the season. Although the overall seasonal applied irrigation depths may match a crop's water demand, farmers often under-irrigate during the early crop stages and over-irrigate during later stages; many choose inadequate timings and application depths. Such inadequate applications may be combined with uneven in-field water distribution, often due to the average low uniformity of irrigation systems—especially when not properly designed, evaluated and maintained; consequently, the farm may have up to 20% lower crop yields and income, along with inefficiencies between 20 and 40% due to excessive water applications (Zaccaria et al., 2010). As the main reason for the mismatch, irrigation scheduling practices are based only on farmers' perceptions and experiences; missing is status monitoring of soil or plant water, use of ET-based irrigation scheduling, or any other quantitative techniques (ibid). This study confirms a general problem of water-inefficient practices, as also found in the wider technical literature (e.g. Hanson et al., 1995, 1996; Burt, 2004; Salvador et al., 2011; see Section 1).

3.2. Innovative practices for stakeholders' consideration

Resource-efficiency could be enhanced by properly utilising several innovative technologies and practices. As listed in Table 1, several feasible options are already installed and implemented in the Sinistra Ofanto area, i.e. along the water conveyance and distribution system or on some progressive farms, but require either some refinements or significant operational improvements to gain their full economic and environmental benefits.

Investment costs for the installed technologies were paid by the WUO either from budget surpluses (in years when water demand and delivery were high), or by funds obtained from different sources, and by some individual farmers at the farm level. Their maintenance and operational costs are paid by growers within the regular water fees. The improved irrigation methods, systems and practices are implemented only to a small extent by some farmers.

The first two technologies were recently installed along the distribution networks to ease operation and flow control, and thus increase its efficiency, but they still need further testing and tune-ups to fully exploit their potential. For example, multi-user hydrants could be hooked up with soil moisture sensors or plant–water status sensors to schedule irrigation applications on the basis of needed or user-defined thresholds and frequency. Also, they could be set to cease water withdrawals and irrigation when the pressure-head values at delivery are insufficient to achieve the target level of efficiency and distribution uniformity. Moreover, relevant datasets from the field (on irrigation timings, flow rates, pressure heads, volume and duration) could be automatically transmitted to a central WUO workstation, thus easing the data-gathering necessary for billing farmers, for evaluating the irrigation delivery service provided and growers' irrigation scheduling practices. These further adjustments of the available technologies could also enable the performance evaluation and benchmarking of irrigation at on-farm and project level.

As indicated by those examples, upgraded technologies alone do not ensure the anticipated resource- efficiency improvements. Compared to less technology-intensive systems, the past

Table 1
Technologies, impacts and necessary improvements.

Technology	Level of application	State of implementation	Action	Impacts	Needs and Improvments
Multi-user electronic hydrants	Distribution network/hydrants	Installed and operated	Supply water to authorised users Control, record and store irrigation events Bill farmers according to used volumes Implement tiered water tariff Programmable to supply water during specific time slots	Simplify water distribution and water billing Reduce WUAoperational cost Responsible water use by farmers Reduce water demand	Data transmission Low-pressure alert High-salinity alert Integration with IAS
Variable-speed pumps	Pumping plant	Recently installed S operated	Adjust their operation dynamically Supply the discharges and pressure heads required by the network	Energy saving Reduce WUO operational costs	Data recording and transmission Accurate system analysis Tuning operational regulation Improve energy-efficiency Better visualisation of benefits
Shift to improved irrigation methods (sprinkle to mini-sprinkle and trickle)	Farm irrigation systems/cropped plots	Recently implemented by some farmers	Reduce soil wetting Reduce soil evaporation losses Reduce energy requirements	Reduce water demand Energy saving Reduce irrigation cost to farmers Reduce overall water abstraction	Technical support and extension Irrigation advisory service Improve application efficiency
Sub-surface drip irrigation (SDI)	Farm irrigation systems/cropped plots	Very limited	Reduce/minimise soil wetting Reduce application losses Increased WP	Reduce water demand Energy saving Reduce irrigation cost to farmers Reduce overall water abstraction	Precision operation Better visualisation of benefits Improve irrigation scheduling Improve application efficiency Technical support and extension Irrigation advisory service
Regulated deficit irrigation (RDI)	Cropped plots	Very limited	Increased WUE Increased WP	Reduce water demand Energy saving Reduce irrigation cost to farmers Reduce overall water abstraction	Soil and plant water status monitoring Precision irrigation Better visualisation of benefits Technical support and extension Irrigation advisory service

investments incur extra costs but bring uncertain gains. The full potential benefits depend on adequate management practices, in turn dependent on better expertise, skill-gap assessment, auditing monitoring and evaluation, control systems and extension programmes, including mission-oriented research and outreach.

The above technology options (in Table 1) were presented at the EcoWater project workshop, held in the case study area and attended by diverse stakeholders involved in the Sinistra Ofanto water-system value chain. These included: the River Basin Authority, the WUO, the Apulia Regional Administration, the regional Department of Water Resources, the Ente Irrigazione, ARPA Puglia, CNR-IRSA (Water Research Institute), University of Bari, etc. Stakeholders, decision-makers and experts were asked to share their visions about water management in the area. The discussion identified several issues, emphasising the need for measures to protect groundwater.

As many comments there highlighted, in the last three decades contradictory interests have generated conflicts over water allocation and use. Surface-water availability for agricultural use has been reduced by several factors: expansion of the command areas, incentivised partly by irrigation systems and by regional policies; greater water demands of the municipal, industrial and tourist sectors; and adverse environmental-climatic changes. Participants mentioned several solutions, in particular: monitoring and control of water use should be strengthened throughout the Apulia region,

especially in the study area, in order to avoid aquifer over-exploitation and uncontrolled withdrawals from water courses; deficit irrigation management, already practiced in the study area by some innovative growers, offers a feasible option to enhance water-use efficiency and productivity; and, finally, farmers should share their personal experiences and knowledge in order to help others to use irrigation water in a sustainable and efficient way (reported in [Ecowater, 2013](#)).

In addition, CBC (local WUO) representatives emphasised the importance of using non-conventional water sources as an additional supply, especially the re-use of treated wastewater (TWW) as a valid alternative to aquifer exploitation for irrigation purposes. TWW re-use has several barriers: stringent quality criteria set by regulations for water reuse in agriculture; the high cost of treatment and water conveyance from the treatment plants to agricultural areas; and inadequate research dissemination, even disinformation; and reluctance by farmers. Consequently, TWW re-use should be fostered by several means – lowering the water-quality restrictions, installing the latest technologies available on the market for wastewater treatment to reduce costs of treatment plants, and broadly disseminating research findings to growers, especially through extension activities and farmers' advisers – according to the WUO representatives (reported in [Ecowater, 2013](#)). No stakeholder raised concerns about aquifer characterisation, safe-yield assessment, groundwater

recharge or agrochemicals' fate in soil and aquifers, or farm-level performance assessment of agricultural water management practices.

As emerged during the stakeholder discussion, some future visions may be based on doubtful assumptions. In particular the CBC staff and farmers' representatives assumed that Sinistra Ofanto farmers already achieve high irrigation and water-use efficiency, simply on grounds that they use microirrigation methods. From this assumption, there would be little scope or incentive to growers for further improvement in farm-level water management.

From CBC technical reports over at least a decade, no recent information is available on whether the farm irrigation systems are properly designed, installed, operated and maintained—nor on whether irrigations are adequately scheduled and conducted by growers. Likewise the WUO has not recently fostered irrigation systems evaluations regarding the actual application efficiency and distribution uniformity achieved by growers, or WUE/WP for the various crops and irrigation methods, on the basis of quantitative measurements. Agricultural extension activities have been significantly limited in the last decade by budget constraints. So the CBC lacks an empirical basis for its efficiency assumptions about current performance of on-farm water management. In all those ways, the CBC's practical responsibility ends at the farm gate.

Moreover, responsibility for water-supply problems is displaced onto public-sector agencies, especially for additional water supplies via wastewater reuse. This option is simpler and perhaps more profitable for farmers and the CBC, especially if public bodies carry the main financial burden. Water reuse involves complex issues needing careful investigation and management, in particular: different water qualities may be required, contingent on the final water uses. Water that needs to be buffered or stored for seasonal reuse (e.g. groundwater banking or surface storage) may have other quality requirements than water used for a direct agricultural reuse. And there are potential risks to health and environment (WssTP, 2013: 19–20).

4. Monte Novo case

In Portugal's Alentejo the Monte Novo irrigation perimeter provides abundant water for a rising number of farmers, served by the larger Alqueva reservoir and irrigation project. Dating from 2009, the scheme set initially low water prices to incentivise irrigation by farmers—but without their involvement in discussing implications for crop choices, irrigation practices, farming profitability and expected income. The highly-discounted water price has incentivised crops with high water demands as well as agrochemical inputs, thus creating pollution problems. As mandated by law, the water price will rise significantly towards full-cost recovery by 2017, thus potentially stimulating practices which need less water. What are the prospects for water efficiency improvements?

4.1. Irrigation patterns and future price rise

Since the 1960s Portugal has had plans to irrigate relatively arid areas of the Alentejo, especially to increase employment and livelihoods. Spain's 1993 National Hydrologic Plan was proposing to abstract more of the shared water from the adjoining region, partly on grounds that Portugal was not using the water, but Portugal objected. To avoid such trans-border conflicts, the 1998 Albufeira Convention aimed to protect freshwater and groundwater, as well as the sustainable use of shared water resources, in the context of the negotiation process for the Water Framework Directive (Maia, 2000; Pulwarty and Maia, 2013). Under the Convention, for example, Spain guarantees annual stream flows to Portugal in normal years (Costa, 2003).

The Albufeira Convention facilitated Portugal's Alqueva Multipurpose Project—the Empreendimento de Fins Múltiplos de Alqueva (EFMA). The EU Structural Funds were expected to pay more than half the investment cost (Vergés, 2001). The 1993 EFMA plan combined a reservoir, hydroelectric dam and irrigation networks, thereby helping to justify Portugal's claim on the water. The project aimed to promote the development of a poor, deprived region through irrigated agriculture, electricity production and tourism. Together these were meant to ensure the sustainability of the project in its early phase (Santos et al., 2011).

From the start the EFMA was criticised as a hydrodinosaur—for accepting engineers' assumptions about future water needs, requiring enormous electricity to transport water and so raising the full cost (Costa, 2003). Before EFMA's operation, maize production had greatly risen alongside greater dependence on CAP subsidies for economic viability. The Agriculture Minister hoped that the Alqueva would irrigate industrial crops such as tomato and sugar beet (Vergés, 2001: 7). By using cheap water from the Alqueva dam, some Alentejo farmers were expecting to capture greater payments from the CAP 1st pillar. So they opposed mid-term reforms decoupling such payments from production levels; so did the Portuguese government (Costa, 2003: 26).

According to its promoters, the Alqueva system will foster significant regional development in Alentejo, both in social and economic terms, due to the strategic water reserve and the associated hydraulic infrastructures. The main objective is to guarantee an adequate volume and quality of water to users, especially irrigation water. Further objectives include the energy hydropower production, urban water supply, ecological conservation and recreational uses (EDIA, 2011).

With its geographical topography and high elevation, the Alqueva scheme was an expensive investment (Costa, 2003), especially relative to the small number of farmers who initially joined the scheme. This arrangement resulted in a high unit cost for the water supply. This has high political-economic stakes, given that full-cost recovery of irrigation systems is required by the Water Framework Directive (EC, 2000).

Irrigation delivery service is provided by the public company EDIA (Empresa para o Desenvolvimento das Infraestruturas de Alqueva), the agency responsible for the Alqueva project development and exploitation. Water is abstracted from the Alqueva reservoir and transported through a network of canals and ducts, from primary network to secondary network through hydrants to farmers. Within the larger Alqueva project, the Monte Novo irrigation perimeter is located in Alentejo district, near Évora municipality. The perimeter provides water for irrigation to an area of at least 7800 ha, while the Alqueva Project will have a total 115,000 ha expected capacity by 2015.

In the Guadiana region including Monte Novo, the tertiary sector has 76% of gross value added (GVA) and 67% of employment; the most important sources are tourist accommodation, catering and public services. The agricultural sector has 10% of the region's GVA and about 15% of the jobs; average farm size is large (55 ha). These characteristics, associated with the high proportion of farmers in a company structure, indicate the region's high potential to develop agricultural activities, especially with the full operation of the Alqueva project. But its agricultural activities have a very low competitiveness and a low productivity per unit area; incomes are greatly supported by public subsidies, which comprise about 65% of the total gross margin (ARH-Alentejo, 2011).

In the study area, the major irrigated crops are olives, maize, arable crops (mostly pasture) and horticultures (mostly tomatoes). Farm size ranges from less than 50 ha to more than 500 ha. The largest areas belong to important multi-crop farms, such as the ones owned by the Fundação Eugénio de Almeida (FEA), or the olive

farms owned by Olivais do Sul (ODS); together they comprise more than 30% of the irrigated area in Monte Novo irrigation perimeter.

Fertilisers and pesticides are applied to all crops, especially tomatoes and maize. Greater irrigation stimulates run-off, leach-outs of fertilisers and pesticides and soil erosion. Together these practices reduce soil organic matter, soil fertility and its capacity to retain water, in turn increasing potential irrigation inefficiencies and need for better water management for the same cultivation level as before. Indeed, land degradation and nutrient depletion significantly constrain opportunities to increase water efficiency (Molden et al., 2010; IST, 2013).

In 2009 the WUO Associação de Beneficiários de Monte Novo (henceforth ABMN) was established, representing all farmers connected to the Alqueva water distribution system from EDIA. According to the regulatory Decree Law 84/82, the Association has formal recognition by the Ministry of Agriculture, Trade and Fisheries. The ABMN has the role to promote the administration of constructing the hydro-agricultural development. Nonetheless EDIA has carried out the management and operation of the irrigation perimeter, as well as the investments in constructing the irrigation network.

Water prices are differentiated according to the pressure heads provided at farm-gate delivery. Prices are lower in low-pressure blocks, where water is conveyed and distributed by gravity, generally to larger farmers; irrigation inside farms is within farmers' management. Prices are higher in high-pressure blocks, which are supplied by pumping stations; these reduce the need for farmers to bear the costs of farm-level booster pumps. However, in the high-pressure blocks some large farms need their own investment in irrigation equipment and distribution infrastructures. In some cases farmers already invested in important irrigation infrastructures prior to the construction of the Monte Novo irrigation perimeter. In both cases a higher water price is imposed on important farmers who will not necessarily benefit from higher pressure heads at hydrants (Rita and Capelo, 2005). Moreover, the difference in water prices between low-pressure and high-pressure blocks is insufficient for covering the necessary investments for constructing the main irrigation infrastructures within low-pressure farms' areas, as well as the corresponding exploitation costs, mainly energy and maintenance (Froes and Rodrigues, 2005).

Given those high costs, full-cost recovery would impede a full transition from rain-fed to irrigated agriculture. To attract farmers into the scheme, a 2010 law set the initial water price at only 30% of full cost. This initial price shifts more of the total cost onto the supplier, while incentivising maize cultivation, which demands relatively large amount of water but gains a higher market price. According to the ABMN (Monte Novo's WUO), the discount price gives farmers 'a certain hope', but many have difficulties to obtain credit, which is necessary for farm-level investment to electrify the cultivated zones (Silva, 2010).

As originally set by law, the low water price will be increased by 10% per year towards full-cost recovery by 2017 (Nuncio and Arranja, 2011). This legislative requirement has become contentious. At its full-cost price, water would comprise 13% of the total cost of maize production. Through their WUOs, farmers have been lobbying the authorities to delay the price rise. According to the Federação das Associações de Agricultores do Baixo Alentejo (regional federation of farmers' associations), the higher price will not allow farmers to be economically competitive, especially for a large proportion of maize cultivation, estimated as more than 36,000 tonnes aimed at export markets. According to the former Agriculture Minister, however, the higher price will be competitive with nearby regions, as an adequate basis for more farmers to join the scheme (Maneta, 2010; Rosado, 2012). The future increase could stimulate water-conserving measures and alternative

cropping patterns which would be more profitable and/or need less water, while also reducing other resource burdens. But continuous support measures would be necessary for growers to evaluate and implement such options.

4.2. Innovative practices for stakeholders' consideration

The on-demand water-delivery system was meant to incentivise water-efficient practices by farmers and thus to reconcile tensions between various objectives of the Alqueva project. Such a strategy put great expectations upon a technological system. At the irrigation-perimeter level the eventual implementation of innovative practices is meant to be supported by the ABMN (WUO), with investment costs if necessary to be covered from budget surpluses. On the other hand, the farm-level water-use improvements are dependent on farmers' own investment or eventually on government subsidies fostering efficiency increases. Some technologies have been applied at farm level, e.g. sub-surface irrigation at FEA and ODS farms, but only to a small extent. Buried drip-irrigation systems need even more careful design, monitoring and operation than surface-drip or other micro-irrigation systems. Beyond the technological investment, greater application would depend on applied research, demonstration activities, outreach, farmers' training and skills development.

The study team assessed various options for lowering input demands (of energy, water, agrochemicals) or for increasing farmers' income per unit water used (Ecowater, 2012), in two main categories as follows. At the irrigation perimeter level, i.e. the distribution network:

- tiered volumetric water tariffs according to actual water use by growers;
- tiered water tariffs according to timing of withdrawals and energy costs, e.g. lower rates at night-time; and
- pressure head delivery.

And at the farm level:

- drip irrigation, reducing water evaporation (especially relevant to maize);
- sub-surface drip irrigation, minimising soil evaporation and facilitating mechanical weed-control or conservation tillage or minimum-tillage methods (especially relevant to vineyards);
- super-high density olive orchards;
- variable-irrigation practices, e.g. through regulated deficit irrigation; and
- alternative crops demanding less water.

The study team presented the above options at an April 2012 workshop. It was attended by representatives and experts from relevant local bodies. They included: EDIA, farmers' representatives (FEA and ODS), the ABMN (WUO), ARH-Alentejo, and the Centro Operativo de Tecnologia do Regadio (COTR), an advisory body for scientific research regarding agricultural development.

Stakeholders' comments converged around the following points:

- All the proposed technologies could add value to the Alqueva scheme.
- Farmers are interested in any technological configuration that might increase their profit margins, which are currently low.
- Given the high investment costs of the irrigation scheme, a successful operation is important in order to lower the unit cost of water through access to more growers (Ecowater, 2013).

Discussion focused on the knowledge lacking for farmers to minimise irrigation intensity and to conserve soil resources. In particular participants made these comments:

- Irrigation intensity must remain within the carrying capacity of the soil (infiltration rate and water-holding capacity), especially in order to prevent surface run-off, leach-outs and erosion—significant environmental impacts that must be taken into consideration.
- Without adequate knowledge for such judgements, farmers may intensify resource usage, thus increasing costs, leach-outs and soil erosion.
- Root-zone soil moisture conditions are not measured to identify in-field variability and vulnerable areas, so most farmers base decisions on their past experience and daily observations of farm conditions.
- Although a network of meteorological stations already exist in the area, relevant information is not available for irrigation planning and scheduling purposes; farmers' access is still under development (Ecowater, 2013).

Regarding the above point about the soil's water-capacity, a COTR expert emphasised soil organic carbon (SOC) as an environmental indicator and objective. Greater irrigation flows undermine the soil's capacity to retain water and nutrients, while also increasing GHG emissions. SOC conservation is more difficult for annual arable crops than for permanent pasture. To avoid further SOC loss and to enhance its role, farmers could incorporate crop residues into the soil and/or choose crops which need less irrigation and chemical inputs. Before any technological change, decision-makers should evaluate the implications for SOC, he argued. This issue was not taken up by other stakeholders at the workshop.

The workshop discussion also considered whether the cultivation of organic crops could be an alternative option, along with bio-labelling to gain a higher market price. According to the ODS representative, farmers would use organic cultivation methods if they could be convinced that their profit would increase. But owners of small farms would not be easily convinced (Ecowater, 2013). Indeed, small-scale growers lack an advisory service and systematic support for linking organic methods with higher-value markets. This institutional gap illustrates wider difficulties for farmers adjusting to new challenges and gaining the full potential benefits of the EFMA.

5. Discussion and conclusions

Innovative irrigation practices can enhance water efficiency, gaining an economic advantage for farmers while also reducing environmental burdens. Water-efficient methods and better irrigation scheduling could also integrate water and nutrient management, thus minimising agrochemical runoff and leaching problems. To help fulfil this potential, experts have developed various models of water efficiency and environmental benefits. Yet these models are little used for irrigation scheduling; at most, they help retrospectively to evaluate seasonal approaches (FAO, 2012).

In that generally adverse context, our two case studies of irrigation schemes investigated options, stimuli and difficulties to improve water-efficient practices. In both cases, individual farmers and/or their organisations already made significant investments in irrigation technologies, but their implementation has not been systematically evaluated for effectiveness through better knowledge—regarding crops' water use, soil-moisture conditions, irrigation scheduling techniques, crops' yield response to different irrigation management strategies, etc. Farmers there have no formal responsibility to demonstrate efficient water use (unlike

in the UK; Knox et al., 2012). Consequently, farmers pay higher water prices yet do not obtain the full potential benefits through water-efficient practices. Reasons why have been investigated by exploring perspectives of water users organisations (WUOs) and relevant agencies, especially through multi-stakeholder workshops.

The two cases have strong stimuli for more water-efficient practices. In the Sinistra Ofanto case, a main stimulus is the prospect of greater water scarcity and erratic supply, leading some farmers to rely on groundwater, which may progressively become more scarce, over-drafted, more expensive due to higher pumping costs, degraded and/or saline. In the Monte Novo case, a water-abundant system, a main stimulus is the statutory rise in water price towards full-cost recovery; this would weaken the commercial viability of some crops with high water demand, such as current maize cultivation.

Anticipating such future difficulties, stakeholders have discussed options for better practices. In each area, stakeholder representatives attended our project workshop on how farmers' economic advantage could be combined with environmental benefits. Despite the stimuli for more water-efficient practices, however, actors' responsibility has been somewhat displaced onto hypothetical prospects. In particular, for the two areas:

At the Sinistra Ofanto workshop, stakeholder representatives emphasised problems of water scarcity and aquifer salinity. Their comments suggested various possible measures such as region-wide control and regulation, farm-level practices and farmers' knowledge-exchange systems. At the same time, however, the WUO displaced responsibility onto the prospect of additional supply from wastewater reuse; this would depend on significant institutional, policy and technical changes, with an uncertain timescale and cost.

At the Monte Novo workshop, stakeholder representatives expressed interest in farm-level technological improvements which could improve water efficiency. Yet WUO representatives also emphasised the need to maintain a low unit cost of water. Moreover, the WUO publicly advocates a longer-term low water pricing, which would depend on a legislative change contradicting the country's EU obligations and the original mandate for the irrigation scheme.

In both cases responsibility is displaced, thus complementing WUOs' and farmers' assumption that their agricultural water management practices already have adequate efficiency. This attitude arises by default—from seeing no systematic means or incentive for more water-efficient practices, beyond the modern technologies already adopted. Experts generally have sought to overcome such obstacle through better models of evapotranspiration and efficient water use (e.g. Pereira et al., 2012). Yet such models cannot reconcile stakeholders' different understandings of irrigation efficiency: farmers seek to maximise their economic benefits, while water experts or agencies seek to conserve water (Knox et al., 2012).

Therefore a solution would need a continuous knowledge-exchange with three components:

- i. expert scientific knowledge of crops' water needs, their yield-response to water and the actual on-farm versus attainable efficiency (Hsiao et al., 2007);
- ii. links between farmers' perspectives, innovative practices and their income benefits (Knox et al., 2012); and
- iii. means to lower resource burdens from inputs and pollutants (Miller, 2007).

Relative to such a solution, our two case-study areas have a nominal extension service which lacks the necessary resources, expertise and operational capability in agricultural water management; these services have no external auditing. A

knowledge-exchange system does not exist in those areas, so farmers may miss the full potential benefits of the technological investment already adopted. Under current circumstances, irrigation practices will maintain the unknown efficiency level; along with their WUOs, farmers will have weak capacities to make extra efforts for more water-efficient practices, as well as weak incentives to pay for any further investments.

An adequate knowledge-exchange system would depend on greater institutional responsibility for water-related policies and strategies, for example, through an extension service or a functional equivalent through a WUO. This in turn would provide an enabling condition and incentive for all relevant stakeholders (especially WUOs) to share greater responsibility for agricultural water management across the entire water-supply chain, including farm-level practices as well as drainage and leach-out management. On this basis, more water-efficient practices could combine wider environmental benefits with economic advantage for farmers.

Acknowledgements

This work was supported by the European Commission through the project, 'EcoWater: Meso-level eco-efficiency indicators to assess technologies & their uptake in water use sectors', a collaborative research project of the 7th Framework Programme, grant agreement no. 282882, coordinated by the National Technical University of Athens (NTUA) during 2011–2014, <http://environ.chemeng.ntua.gr/ecowater/>. We would like to thank two anonymous referees of this journal for helpful comments.

References

- Ahearn, M., Yee, J., Bottom, J., 2003. Regional trends in extension system resources. In: *Agricultural Information Bulletin* No. 781. U.S. Department of Agriculture, Economic Research Service, Washington, DC.
- Altieri, S., 1995. The Sinistra Ofanto irrigation scheme: management and maintenance problems. In: Pereira, L.S. (Ed.), *Bonifica*, vols. 1–2. Bastogi Editrice Italiana, Foggia, pp. 40–47.
- ARH-Alentejo, 2011. Planos de Gestão das Bacias Hidrográficas—Região Hidrográfica 7—Relatório técnico para efeitos de Participação Pública, Nemos—Ecosistema—Agro.ges (River basin management plan—Guadiana Technical report for public participation). Administração da Região Hidrográfica (ARH) do Alentejo.
- Battilani, A., 2012. Sustainable Knowledge-based Irrigation Management: The IRRINET package. (<http://ec.europa.eu/environment/archives/greenweek2012/adriano-battilani.html>), (http://ec.europa.eu/environment/archives/greenweek2012/sites/default/files/3-9_battilani.pdf).
- Battilani, A., 2013. Approaches to Improve the Productivity of Water Use in Irrigation [with diagrams]. (<http://www.wsstp.eu/files/WSSTPX0001/IL2.%20Adriano%20Battilani.pdf>).
- Benham, B.L., Linder, G.M., Hinrichs, M.D., 2000. Improving irrigation management in Nebraska's central Platte valley. *J. Nat. Res. Life Sci. Educ.* 29, 111–115.
- Burt, C., 2004. Rapid field evaluation of drip and microspray distribution uniformity. *Irrig. Drain. Syst.* 18, 275–297.
- Caswell, M., Zilberman, D., 1985. The choices of irrigation technologies in California. *Am. J. Agric. Econ.* 67 (2), 224–234.
- CBC, 1984. Consorzio di Bonifica per la Capitanata, Cinquant'anni di bonifica nel Tavoliere. Bastogi Editrice, Foggia.
- CEC, December, 2008. Follow up Communication on Water Scarcity and Droughts in the European Union COM (2007) 414 final, [SEC(2008) 3069]. Commission of the European Communities, Brussels.
- COPA-COGECA, 2007. COPA-COGECA Position on Water Scarcity and Drought. COPA (Committee of Professional Agricultural Organisations), General Confederation of Agricultural Cooperatives (COGECA), Brussels, (<http://www.copa-cogeca.be/Menu.aspx>).
- COPA-COGECA, 2013. Water and Agriculture under a Changing Climate. COPA-COGECA.
- Costa, L., 2003. A Portuguese Hydrodinosaur: The Hidden Costs of the Alqueva Dam. (http://www.hydrologie.org/hydrodinosaur/download/portugal_ang.pdf).
- EC, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy. EC.
- Ecowater, 2012. Deliverable 1.2: Value Chain Mapping of the Agricultural Water Systems. Ecowater, EcoWater project, (<http://environ.chemeng.ntua.gr/ecowater/Default.aspx?t=238>).
- Ecowater, 2013. Deliverable 6.1: Synthesis report from the 1st Round of Case Study Events. Ecowater, (<http://environ.chemeng.ntua.gr/ecowater/Default.aspx?t=238>).
- EDIA, 2011. Portal de mapas (Map Portal). EDIA, (<http://www.edia.pt>) (last visit in December 2011).
- EIO, 2011. Water Innovation: How Eco-innovation can Contribute to the Sustainability of Europe's Water Resources. Eco Innovation Observatory.
- EP, 2008. Addressing the challenge of water scarcity and droughts in the European Union. European Parliament resolution of 9 October 2008 on addressing the challenge of water scarcity and droughts in the European Union (2008/2074/INI).
- Fabiani, S. (ed.), 2010. Aspetti economici dell'agricoltura irrigua in Puglia. Istituto Nazionale di Economia Agraria (INEA), (<http://dspace.inea.it/bitstream/inea/520/1/SE5-1164.pdf>).
- FAO, 2012. FAO Irrigation and Drainage Paper 66: Crop Yield Response to Water. (<http://www.fao.org/nr/water/infores.html>).
- Faurès, J., Svendsen, M., Turrall, H., 2007. Reinventing irrigation. In: Molden, D. (Ed.), *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*. Earthscan and International Water Management Institute, London, Colombo (Chapter 9).
- Fraiture, C., Perry, C., 2007. Why is agricultural water demand unresponsive at low price ranges? In: Molle, F., Berkoff, J. (Eds.), *Irrigation Water Pricing: The Gap between Theory and Practice*. CABI, Wallingford, pp. 94–107.
- Froes, J., Rodrigues, P.N., 2005. Distribuição de água em baixa pressão no Alqueva. In: *Paper in I Congresso da Rega e Drenagem*. Beja, Portugal, Available in (www.cotr.pt/informacao/web2/Papers/48.pdf).
- García-Vila, M., Fereres, E., 2012. Combining the simulation crop model AquaCrop with an economic model for the optimization of irrigation management at farm level. *Eur. J. Agron.* 36, 21–31.
- Genius, M., Koundouri, P., Nauges, C., Tzouvelekas, V., 2014. Information transmission in irrigation technology adoption and diffusion: social learning, extension services, and spatial effects. *Am. J. Agric. Econ.* 96 (1), 328–334.
- Gold, A.J., Parker, D., Waskom, R.M., Dobrowolski, J., O'Neill, M., Groffman, P.M., Addy, K., 2013. Advancing water resource management in agricultural, rural, and urbanizing watersheds: why land-grant universities matter. *J. Soil Water Conserv.* 68 (4), 337–348.
- Hanson, B., Bowers, W., Davidoff, B., 1995. Field performance of microirrigation systems. In: *Microirrigation for a Changing World*. Proceedings of Fifth International Microirrigation Congress, April 2–6, 1995. American Society of Agricultural Engineers, Orlando, FL, pp. 769–774.
- Hergert, G.W., Penas, E.J., Ferguson, R.B., Cahoon, J.E., Klocke, N.L., Watts, D.G., Shapiro, C.A., Peterson, T.A., 1994. Extension programming for improving nitrogen and irrigation management in Nebraska. In: *National Symposium on Protecting Rural America's Water Resources: Partnerships for Pollution Solutions*, Washington, DC.
- Hanson, B., Bowers, W., Davidoff, B., Kasapligil, D., Carvajal, A., Bendixen, W., 1996. Field performance of microirrigation systems. In: *Proceedings of the Fifth International Microirrigation Congress*, Orlando, FL, pp. 769–774.
- Howell, T.A., 2003. Irrigation efficiency. In: *Encyclopedia of Water Science*, (<http://dx.doi.org/10.1081/E-EWS-120010252>), (http://www.researchgate.net/publication/43256707_Irrigation_Efficiency).
- Hsiao, T.C., Steduto, P., Fereres, E., 2007. A systematic and quantitative approach to improve water use efficiency in agriculture. *Irrig. Sci.* 25, 209–231.
- Iglesias, E., Blanco, M., 2008. New directions in water resources management: the role of water pricing policies. *Water Resour. Res.* 44 (6), 1–11, (<http://dx.doi.org/10.1029/2006WR005708>).
- Irmak, S., Odhiambo, L.O., Kranz, W.L., Eisenhauer, D.E. 2011. Irrigation Efficiency and Uniformity, and Crop Water Use Efficiency, Lincoln, NB: University of Nebraska–Lincoln Extension, (<http://extension.unl.edu/publications>).
- IST, 2013. Avaliação Ambiental Estratégica dos novos investimentos EFMA relativos à Rede Secundária de Rega, no âmbito do INALENTEJO (Strategic Environmental Assessment of new EFMA's Investments). In: *Relatório preliminar: Relatório Ambiental*. Instituto Superior Técnico (IST), Lisboa, Available online at (<http://www.inalentejo.qren.pt/images/stories/file980.pdf>).
- Kampas, A., Petsakos, A., Rozakis, S., 2012. Price-induced irrigation water saving: unravelling conflicts and synergies between European agricultural and water policies for a Greek water district. *Agric. Syst.* 113 (1), 28–38.
- Knox, J.W., Kay, M.G., Weatherhead, E.K., 2012. Water regulation, crop production and agricultural water management—understanding farmer perspectives on irrigation efficiency. *Agric. Water Manage.* 108 (1), 3–8.
- Luquet, D., Vidal, A., Smith, M., Dauzat, J., 2005. More crop per drop: how to make it acceptable for farmers? *Agric. Water Manage.* 76 (2), 108–119.
- Maia, R., 2000. Portuguese–Spanish river basins: bilateral agreements' evolution and context. *Water Sci. Technol.* 42, 227–233.
- Maneta, L., abril, 2010. Preço da água de Alqueva não convence agricultores. In: *Diário de Notícias*, (http://www.dn.pt/inicio/economia/interior.aspx?content_id=1540958).
- Miller, A., 2007. Environmentally Sustainable Agri-Food Production. Environmental Sustainability Knowledge Transfer Network (ESKTN).
- Molle, F., Berkoff, J., 2007. Water pricing in irrigation: the lifetime of an idea. In: Molle, F., Berkoff, J. (Eds.), *Irrigation Water Pricing: The Gap between Theory and Practice*. CABI, Wallingford, pp. 1–20.
- Molle, F., 2008. Can water pricing policies regulate irrigation use? In: *13th World Water Congress*, September, Montpellier, France.
- Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: between optimism and caution. *Agric. Water Manage.* 97, 528–535.

- Nuncio, J., Arranja, C., 2011. *Gestão dos aproveitamentos hidroagrícolas de Alqueva*. Jornadas Técnicas APRH, (http://sir.dgadr.pt/conteudos/jornadas_aph/apresentacoes/s7/11.pdf).
- Parker, D., Cohen, D., Osgood, D., Zilberman, D., 2000. Publicly funded weather database benefits users statewide. *Calif. Agric.* May–June, 21–25.
- Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agric. Water Manage.* 108, 39–51.
- Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. *Agric. Water Manage.* 96, 1517–1524.
- Portoghesi, I., D'Agostino, D., Giordano, R., Scardigno, A., Apollonio, C., Vurro, M., 2013. An integrated modelling tool to evaluate the acceptability of irrigation constraint measures for groundwater protection. *Environ. Modell. Softw.* 16, 90–103.
- Pulwarty, P., Maia, R., 2013. Adaptation challenges in complex river basins around the world. In: Eighth International Conference of EWRA, Water Resources Management in an Interdisciplinary and Changing Context, 26–29 June, Porto, Portugal.
- Rita, C., Capelo, O., 2005. Distribuição em alta pressão vs. distribuição em baixa pressão num bloco de rega do E. F. M. Alqueva (Monte Novo). In: Paper in I Congresso da Rega e Drenagem, Beja, Portugal, (Available in www.cotr.pt/informacao/web2/Papers/38.pdf).
- Rosado, L., 2012. A cultura do milho na Fundação Eugénio de Almeida. In: VIII Congresso Nacional do Milho, Lisboa.
- Salvador, R., Martínez-Cob, A., Cervero, J., Playán, E., 2011. Seasonal on-farm irrigation performance in the Ebro basin (Spain): crops and irrigation systems. *Agric. Water Manage.* 98, 577–587.
- Santos, J.F., Gomes, J.C., Fialho, I., 2011. Contributo para a discussão das condições de sustentabilidade da component hidroagrícola do EFMA, Jornadas Técnicas APRH, Lisboa, LNEC, 12–15 Outubro, http://sir.dgadr.pt/conteudos/jornadas_aph/apresentacoes/s2/32.pdf, Technical Days index at <http://sir.dgadr.pt/jornadasapr>
- Silva, A.M., 2010. Alqueva: água baixa 70% para agricultores, *Correio da Manhã*, 11 abril, <http://www.cmjornal.xl.pt/detalhe/noticias/nacional/economia/agua-baixa-70-para-agricultores>, <http://boasnoticias.sapo.pt/mobile/noticias.php?id=771>
- Sinclair, T.R., Tanner, C.B., Bennett, J.M., 1984. Water-use efficiency in crop production. *BioScience* 34 (1), 36–40.
- Steduto, P., 2007. On the conservative behaviour of biomass water productivity. *Irrig. Sci.* 25 (3), 189–207.
- Tollefson, L.C., Wahab, M.N.J., 1994. Better Research-Extension-Farmer Interaction can Improve the Impact of Irrigation Scheduling Techniques. World Bank, Washington, DC.
- Vergés, J.C., 2001. The Alqueva Irrigation Agreement (Study subcontracted to Modern Consultant S.L. by Research Contractor WRC plc, for the Environment Agency, UK).
- WBCSD, 2000. Eco-efficiency. In: Creating More Value with Less Impact. World Business Council for Sustainable Development, (http://www.wbcd.org/web/publications/eco_efficiency_creating_more_value.pdf).
- WssTP, 2012. Irrigated Agriculture Water Saving Options in Irrigation, Looking for Efficient Techniques, Irrigation Management and Adapted Cropping Practices. Water Supply and Sanitation Technology Platform (WssTP), (<http://www.wssTP.eu/files/WSSTPX0001/library/agriculture/SP%20Agriculture%20VI.pdf>).
- WssTP, 2013. Water Reuse: Research and Technology Development Needs for Water Reuse. WssTP, Summary at (<http://www.wssTP.eu/files/WSSTPX0001/Water%20Reuse%20Ex.Summary%20online.pdf>).
- Zaccaria, D., Oueslati, I., Neale, C.M.U., Lamaddalena, N., Vurro, M., Pereira, L.S., 2010. Flexible delivery schedules to improve farm irrigation and reduce pressure on groundwater: a case study in southern Italy. *Irrig. Sci.* 28, 257–270.
- Zaccaria, D., Lamaddalena, N., Neale, C.M.U., Merkley, G., 2013. Simulation of peak-demand hydrographs in pressurized irrigation delivery systems using a deterministic-stochastic combined model. Part II: Model applications. *Irrig. Sci.* 31, 193–208.