Understanding irrigation water use efficiency at different scales for better policy reform: a case study of the Murray–Darling Basin, Australia

M. Ejaz Qureshi[a,b], R. Quentin Grafton[c], Mac Kirby[d] and Munir A. Hanjra[e]

[a]Corresponding author. CSIRO Sustainable Ecosystems, P.O. Box 284, Canberra, ACT 2601, Australia.
Fax: + 61 2 6242 1705. E-mail: Ejaz.Qureshi@csiro.au
[b]Fenner School of Environment and Society, Australian National University, Canberra, ACT 2601, Australia
[c]Crawford School of Economics and Government, The Australian National University, Canberra, ACT 0200, Australia
[d]CSIRO Land and Water, P.O. Box 1666, Canberra, ACT 2601, Australia
[e]International Centre of Water for Food Security, Charles Sturt University, Wagga Wagga, NSW 2678, Australia

Abstract

This paper examines water use efficiency and economic efficiency with a particular focus on the Murray–Darling Basin of Australia and the stated policy goal of increasing environmental flows of water in the Basin. The different measures of efficiency are explained, and their implications for water reform and the efficacy of market based approaches to addressing the water scarcity issues and environmental flow needs are explored. Public policies to subsidize investments for improvements in irrigation efficiency are shown not to be currently cost effective compared to alternatives, such as buying water through water markets. The implications of these findings, and the factors that determine the demand for irrigation water by competing uses, can guide policy makers undertaking water reforms in the agricultural sector to mitigate the environmental consequences of overuse of water resources.

Keywords: Environmental flows; Fixed asset; Irrigation; Risk and uncertainty; Water trading

1. Introduction[1]

Increasing water scarcity and competition for water across sectors is generating an increased focus on the promotion of efficiency in consumptive water use, especially in irrigation (Clemmens & Molden, 2007). However, the technical concepts related to water use efficiency (Clemmens *et al.*, 2008), methods and technological potential to improve water use efficiency (Evans & Sadler, 2008), and conservation

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[1] In this paper, all values are in Australian dollars (AUS$1.00 = US$0.93 as on 22 April 2010).

potential of agricultural water conservation subsidies differ (Huffaker, 2008), and the terminology for this debate in particular remains poorly defined (Perry, 2007). Using the Murray–Darling Basin (MDB) in Australia as a case study, this paper explores the different concepts of water efficiency in terms of irrigation and provides insights to guide policy makers in terms of water scarcity and overuse.

The MDB covers more than one-seventh (or 1 million km^2) of Australia. It is Australia's most important agricultural region, accounting for more than 40% of the gross value of Australian agricultural production and uses 60% of all irrigation water in the country (CSIRO, 2008). Prior to the current drought, the largest users of water for irrigation in the MDB were dairy, followed by cotton, rice, cereals, grapes and other fruits (Bryan & Marvanek, 2004).

The MDB shares a number of characteristics with other major river basins in the world. First, irrigation allowed the expansion of agriculture by stabilising the production, especially of perennial activities (such as citrus and grapes). Second, regional communities have developed that are dependent on irrigation for farming to maintain their way of life and services. Third, there is evidence that water allocation for consumptive purposes (including irrigation) is large and is imposing high environmental costs in terms of deterioration of wetlands, loss of trees and declining biodiversity (Charters & Williams, 2006). In particular, the river systems are facing multiple threats, including changes to natural flow regime, habitat destruction, increased salt and sediment load, and loss of connectivity due to structural alterations and unsustainable floodplain management (CRCFE, 2003).

Policy makers have several economic and policy instruments to provide incentives to irrigators for sustainable land and water management practices (Ward, 2007, 2009; Khan & Hanjra, 2008). For instance, the rationale for water reform (including water markets and water trading) is that some water could be used more productively than in its current use. Water markets and trading provide incentives for an efficient allocation of water across competing uses.

The objective of this paper is to explain the concepts of irrigation efficiency, basin efficiency and economic efficiency, as well as the factors that determine the demand for irrigation water by competing uses (in Sections 2 and 3). The paper also discusses implications for water reform and the importance of achieving an economically efficient allocation of water across competing uses (in Section 4). The implications for further water reform in the Basin and some key conclusions on the importance of achieving an economically efficient allocation of water across competing uses are provided in the closing section.

2. Irrigation efficiency and water trading

2.1. Irrigation efficiency

Burt et al. (1997) presents a comprehensive discussion on various efficiency measures related to irrigation. Several authors have noted that the use of the term 'efficiency' often leads to misconceptions and misunderstandings, especially when increasing efficiencies is equated with creating more available water (Jensen, 2007; Kassam et al., 2007; Molden et al., 2007; Perry, 2007), and when water quality issues are involved (Ayars & Schoneman, 2006).

In reference to irrigation, efficiencies can be defined in terms of the irrigation subsystems: storage, conveyance, off- and on-farm distribution, and on-farm application subsystems, as the ratio between the water delivered by the particular subsystem and the water supplied to that subsystem, usually being

expressed as a percentage. Therefore, a 'total' system efficiency is the product of the various efficiencies of the respective subsystems (Hsiao *et al.*, 2007). Clearly, such a crude measure can provide only limited guidance to underpin water policy decisions, especially when water quality and environmental implications are involved.

Irrigation specialists have used the term water use efficiency to describe how effectively water is delivered to crops and to indicate the amount of water lost. Of the water applied for irrigation, only a fraction is actually consumed by the crop, in the form of evapo-transpiration (Steduto *et al.*, 2007); the rest runs off the field (runoff), soaks into the soil, and percolates to the groundwater (Molden *et al.*, 2007). Thus the concept of physical irrigation efficiency has developed, being the fraction (always less than one) of water consumed usefully by the crop to which it is applied. In broad terms, it is the ratio of the irrigation water consumed by the crops of an irrigation farm or project to the water diverted from a river or other natural water source into the farm project canal or canals (Israelson, 1950; Burman *et al.*, 1983).

Irrigation efficiency may be defined at different operations, scales, or for different components of the irrigation system. Bos & Nugteren (1990) identified three separate operations, namely conveyance, distribution, and field application. Fairweather *et al.* (2003) identified four elements: storage, conveyance and distribution, field, and whole of system. Water use efficiency is a similar concept but is at a different scale, namely, it is the ratio of the amount of water used by the crop to the amount of water applied at the crop level. If the crop water usage is linked to water applied for irrigation then the water use efficiency at that scale determines how much water is applied and how much is used by the crop. The lower the ratio of crop water usage to applied water, the higher the drainage losses and greater the possibility to improve water use efficiency. A summary of all the physical efficiency related terms, along with their definitions, is presented in Table 1.

At the crop or field level, the water 'lost' (i.e., not consumed by the crop) is a small fraction of water that is diverted for irrigation and applied to the field. Crop water usage is generally considered more efficient when most of the applied water is used by the crop. It might seem that a perfectly efficient system, in which all the applied water is used by the crop, is desirable. However, applied irrigation water always contains salts, however small the concentration, and these must be leached from the root zone (Kijne, 2006). Thus, some modest fraction of loss, termed a 'leaching fraction', is necessary, and water use efficiencies above 90% at the field scale are not desirable. This leaching fraction varies across agricultural activities and depends on soil type, location and the on-farm crop irrigation system (Corwin *et al.*, 2007).

Higher irrigation efficiencies, at face value, suggest that more of the applied water is used by the crop and less is lost or wasted. However, surface runoff from a farm can be captured directly for use by another farm, or run back to a river or surface water source where it can be reused, or it may move downward through soil strata to an aquifer for later use (Khan & Hanjra, 2008). Thus, unaccounted downstream recovery of 'waste' drainage water, the recharge and subsequent extractions of groundwater that contribute to downstream allocations, and reuse can result in actual basin-wide efficiencies substantially higher than the nominal values for its constituent irrigation systems (Clemmens & Molden, 2007). Consequently, the potential gains from improving agricultural water use efficiency may be marginal (Seckler, 1996) or even negative if the incentive policies and funds used to improve such efficiency can generate a higher net return to investments in another activity. Also, the investments to 'save' the 'wasted' water in such cases can impact on the health of river systems and their associated environments and ecosystem services (Gordon *et al.*, 2009). Therefore, a comprehensive analysis in a basin context is needed (Molden *et al.*, 2007).

Table 1. Key physical and economic efficiency terms used.

Term	Definition
Physical terms	
Basin-level efficiency	The ratio of crop water evapo-transpiration to total water depletion for irrigation in the basin, which accounts for the potential reuse of return flows and the potential decline in the water quality of return flows.
Effective irrigation efficiency	An alternative term of measuring irrigation efficiency at a basin-scale that takes into account the quantity of water delivered from and returned to a basin's water supply, which is potentially reused by other irrigators downstream (see irrigation efficiency).
Environmental flows	Water flows in streams and rivers used to maintain ecosystem services.
Irrigation efficiency	The ratio of water volume beneficially used by plants to the volume of water delivered through an irrigation system, adjusted for effective rainfall and changes in the water storage in the root zone.
Non-consumptive use	The use of the environment (such as photography or swimming) that, in general, does not detract from its amenity and other values.
On-farm efficiency	The relationship between the amount of water delivered to a farm and the amount of water actually used by the crops.
Return flows	The water returned to a water system via seepage and runoff.
Seasonal allocation	A yield or allocation of water to holders of entitlements that is allocated for a given cropping season.
Water entitlement	A property right that entitles the holder to access water allocations in perpetuity. Different levels of security or reliability of property rights generate different yields or allocations.
Water-use efficiency	The ratio of the amount of water used by a crop to the amount of water applied.
Economic terms	
Allocative efficiency	Cost minimization of inputs in a production process.
Diminishing returns	A term used to describe the decline in the marginal product associated with the increased use of one input (such as water), holding all other inputs constant.
Economic efficiency	For a firm, it is the maximum output produced from a given set of inputs and at minimum cost whatever the level of production. At a societal level, it represents an allocation of resources and factors of production that maximizes the difference between its total benefits from production less the total costs (including private and external) of production.
Externality (negative)	The external cost imposed on others from private or individual actions that are not taken into account by individuals.
In-situ value	The value of an environmental asset (such as water in a river or aquifer) in its natural state.
Marginal product	The extra output or product from the addition of a unit of a variable input.
Net present value	The sum of the discounted net returns (revenues less costs) from a capital investment.
Opportunity cost	The value of what must be given up or sacrificed when undertaking a particular action/investment.
Salvage value	The value of an asset at the end of its working life.
Scale efficiency	Output at a scale that maximizes profits for a firm and where capital and infrastructure can be set to their profit-maximising levels.
Technical efficiency	The maximum possible output given the applied level of inputs in a production process.
Value of marginal product	The price of the output multiplied by the extra output produced from an additional unit of an input.

2.2. Basin-level efficiency

Basin-wide irrigation efficiency is defined in the same way as on-farm crop irrigation efficiency: it is the water used by the crop expressed as a fraction of the water diverted. It may be a large fraction even when the efficiency at a farm or district level is low, as the losses in one farm or district may reappear

downstream and be utilized by another farm or district. Effective irrigation efficiency is yet another term and is used at the scale of the irrigation district rather than the basin level. It redefines irrigation efficiency in terms of net use, that is, the amount of water used as a fraction of that diverted *less* that returned for reuse (Keller *et al.*, 1996). Basin-wide efficiency is the same concept but applied at the basin scale and explicitly accounts for reuse.

In the Nile river basin, studies have shown that the irrigation efficiency of individual irrigation districts is low, at around 30%. However, re-use downstream of the 'lost' water raises the overall basin efficiency to around 80% (Keller, 1992). In the MDB, irrigation efficiencies are estimated at between 60–85% (ANCID, 2007), based on gross diversions. Return flows are estimated to be between 1–2% for the most efficient systems, rising to 8% in some of the larger irrigation areas in the southern parts of the basin, and as high as 20% in some smaller areas (van Dijk *et al.*, 2006). Assuming that the average return flow is 12% while irrigation efficiency is 65%, the effective irrigation efficiency for the MDB is about 70%. The much greater difference between irrigation (about 30%) and effective irrigation efficiency (about 80%) in the Nile arises from the much greater fractions of return flows (at the irrigation district level). Given that basin-wide irrigation efficiency is high in both cases, the scope for overall water efficiency improvements may be limited.

The concept of basin efficiency has enhanced policy analysis by broadening the perspective with which water uses are evaluated and the reuse of surface runoff and deep percolation are accounted for (Wichelns, 2002). Whether the returned water can be reused, however, depends on: (a) the amount of return flow relative to water withdrawal; (b) water quality requirements for downstream water uses; and (c) the extent to which return flow can be reused through natural and/or engineering processes, stored in reservoirs or aquifers, and delivered or pumped or used for in-stream committed environmental flow, hydropower generation and for ecological preservation (Keller & Keller, 1995; Keller *et al.*, 1995; Cai *et al.*, 2001).

A major deficiency of basin efficiency is that it focuses only on physical variables (i.e. quantitative and qualitative aspects of water) and ignores the costs and benefits of increasing the physical measure of efficiency. For instance, policy driven investments in improving local efficiency may be wasteful if they simply reduce water in a downstream irrigation region that may be being used for another and possibly higher value crop or for human consumption. Thus increasing water use efficiency at one scale may create winners and losers, and losses may not always be offset by the gains elsewhere. Equity issues across temporal and human scales pose more complex challenges to water policy aimed at efficiency improvements than do spatial issues.

Whether or not decreased irrigation water application translates into real water savings at a basin scale depends on the hydrological interactions between the field, the farm and the entire river basin, as well as on the response of the farmers to the technologies and physical and institutional environment in which they operate (Ahmad *et al.*, 2007). Scaling up the water savings beyond the farm level presents unique opportunities and challenges (Hsiao *et al.*, 2007) in terms of institutional and policy design (Hussain *et al.*, 2007).

2.3. Economic efficiency

Economic efficiency is different to irrigation efficiency. A summary of all the economic efficiency-related terms along with their definitions is given in Table 1. The economic efficiency of irrigation water refers to the economic benefits and costs of water use in agricultural production (Cai *et al.*, 2003) including the costs of water delivery, the opportunity cost of irrigation and drainage activities, and

potential third-party effects or negative (and positive) externalities (Dinar, 1993). Economic efficiency typically has broader policy implications than irrigation efficiency measures, because they enable an analysis of private and social costs and values associated with water use (Dinar, 1993; Wichelns, 1999).

At the individual farm-level, economic efficiency, in the absence of externalities, requires that water use by irrigators be: (a) technically efficient such that from a given amount of water it is not possible to generate a higher output under existing production constraints, infrastructure and technology; (b) allocatively efficient when all inputs including water, in the production process are used in their least cost combinations; and (c) scale efficient such that capital and infrastructure is utilized at levels that maximize profits (Balcombe *et al.*, 2006). Economic efficiency at a farm level ensures that irrigators are 'doing the best they can' in terms of maximizing the net returns from water use. This, however, does not mean that economically efficient irrigators have the highest possible irrigation efficiency. Indeed, it implies that given the existing infrastructure, constraints and technology it is not possible for an irrigator to reduce water use without lowering output (technical efficiency) such that all inputs, including water, are used in their cost minimizing combinations (allocative efficiency), and that the scale of production or farm output minimizes the average costs of production (scale efficiency).

At a catchment or basin level, economic efficiency refers to the notion of a 'potential Pareto improvement' (Huffaker & Whittlesey, 2000; Johansson *et al.*, 2002). A Pareto improvement occurs when all possible water allocations (including the current or status quo allocation) are compared and the question is asked whether it would be possible to move to another allocation from the status quo where those that gain from this change could (but not necessarily do) compensate any potential losers; if the answer is no, then the status quo allocation is economically efficient. An economically efficient allocation of water at a basin or catchment level, therefore, maximizes the difference between: (a) all the benefits associated with all water uses (including 'non-use' or in-situ values for the environment); and (b) minus all the costs including both the private costs of irrigators and the external costs imposed on others from water use such as losses in ecosystem services (Huffaker, 2008).

The concept of economic efficiency ensures that the marginal net benefit (marginal revenue less marginal private and external cost of water) be equalized for all agricultural activities, while accounting for differences in return flows and in-stream effects (Ward & Michelsen, 2002). If marginal net benefits of different water uses are not equal, it is always possible to increase aggregate benefits by transferring water from those activities with low marginal net benefits to those with higher marginal net benefits.

2.4. Water trading and economic efficiency

Water trading (or markets) can be an effective policy mechanism to reallocate water across uses as it provides incentives for an economically efficient allocation of water use and can transfer water from its current (lower value) to more productive (higher value) uses. Water markets also offer advantages in the quest for higher water use efficiency (Jury & Vaux, 2005) if water saving investments can be undertaken at a lower cost than the market price of water.

Water trading has facilitated a major reallocation and reassignment of water between irrigators, helping to optimize irrigation decisions. Water trading can facilitate farm adjustment and structural change within irrigation communities in response to water scarcity (Bjornlund & McKay, 1999). However, it does not guarantee an economically efficient water allocation across all uses. This is because water markets, in general, only consider the value of water in terms of consumptive uses and not its environmental value in terms of its 'in-situ' or 'unused' state. In the absence of an active participant in

the water markets that purchases water for environmental flows and ecosystem services to generate public good values, water will not be efficiently allocated in an economic sense.

An economically efficient and socially acceptable water allocation requires inclusion of the environment in the market, and a market price that accounts for the costs of water use and the external costs imposed on others. This requires clearly defined water rights that are fully transferable with priority to the environment. A difficulty with water rights in the MDB is that they are defined in terms of shares in the total available seasonal water supply rather than net volumetric diversions. This impedes decision making regarding water trading due to uncertain allocations. Also, the water is delivered to farms and charged in gross terms rather in terms of net water consumption. As a result, farmers who use a greater fraction with higher efficiency (say 80%) of their allocated water pay an equal price to others who use a small fraction of their allocated water with lower efficiency (say 40%).

Trading does not always result in net social gains if there are increased negative externalities (effects imposed on third parties) following the trade. For instance, water trading that leads to permanent water transfers out of mature irrigation areas can impact salinity, while causing substantial negative impacts on resource quality, agricultural productivity and on the social well-being of local communities (Khan *et al.*, 2009). Even if water markets fully account for the value of water in terms of the environmental externalities, trading may still not result in an economically efficient outcome if there are restrictions on trade. In Australia, despite progress in the water markets (mainly in temporary trading) there are still significant barriers and restrictions in the functioning of water markets (Qureshi *et al.*, 2009). These restrictions and market frictions are called transaction costs and are the costs of enforcing and exchanging water rights. They include the brokerage, commission and conveyance fees associated with water transfers, the costs of acquiring water market information by both buyers and sellers, and any extra charges imposed on sellers and buyers. Extra charges include exit fees that are sometimes billed to irrigators who permanently trade their water entitlements outside of an irrigation district. These exit fees can be a substantial proportion of the sale price and are regularly applied in some irrigation districts within the MDB (Grafton & Peterson, 2007). In 2008, for instance, Murray Irrigation Limited—the largest irrigation company in the state of New South Wales—imposed a compulsory exit fee of $383/ML (mega litre or 10^6 litres) on water leaving the district. Since exit fees can stifle trade, they have recently been abolished by the Australian Competition and Consumer Commission (ACCC, 2008). In addition to exit fees there are also physical annual limits imposed on how much water can be traded out of an irrigation district that will prevent water trading to its highest value in use. The annual trade limits are currently capped at 4% of the total water entitlements in some parts of the MDB and have been imposed to avoid rapid socio–economic adjustments associated with water transfers.

2.5. Water trading and irrigation efficiency

Water trading can be instrumental in improving irrigation efficiency by creating an explicit price for water and encouraging good use of water on farm. Whether irrigators choose to purchase water or not, a market price for water represents an opportunity cost to an enterprise in the sense that it could have sold its water entitlement, or the water yield or seasonal allocation assigned to the water right, to someone else. Thus, the price of water becomes an explicit cost of production. Consequently, if water savings per volume of water can be realized at a lower cost than the market price then irrigators will, in the absence of other constraints, make such investments and generate water savings in irrigation use. The higher the traded price for water, the greater the incentive to undertake water use saving investments.

The water savings that irrigators can achieve will vary over time. In the very short run there may be little that can be done, except water stressing current crops through deficit irrigation or undertaking minor water efficiency improvements (Lorite *et al.*, 2007). In the long run, farmers have the option of completely refiguring their irrigation infrastructure, technology and crops (Dinar *et al.*, 1992; Brill *et al.*, 1997). The various water saving strategies available to farmers include: (a) changing the variety of a given crop to one that needs less water or can withstand drought; (b) changing the crop mix to include a crop of higher value per unit of water; (c) using less water per hectare through deficit irrigation (i.e. not giving the plants all of the water that they can use, either deliberately or inadvertently); and (d) reverting some area of land to dryland farming or exiting production entirely, and permanently trading water rights where they exist (Zilberman *et al.*, 1994; Kokic *et al.*, 2007; Nelson *et al.*, 2007).

If alternative and cheaper sources of water are available, farmers will be attracted to access these supplies. For instance, until recently in the MDB, farmers could construct small dams to capture the rainfall on their properties and access groundwater at a cheaper price than surface water (Brainwood *et al.*, 2004). A CSIRO study estimated the impact of farm dams on stream flow in the MDB to be around 2,200 GL (giga litres). This resulted in an estimated total stream flow reduction of 1,900 GL per year (van Dijk *et al.*, 2006). Similarly, the impact of current groundwater pumping on stream flow across the MDB is estimated to be 447 GL/year which is expected to increase and subsequently reduce annual stream flow by 840 GL/year (CSIRO, 2008).

In addition to the price of water, an irrigator will also consider the volume of production and the price per unit of output when determining the optimal amount to invest in increasing irrigation efficiency. The desired level of irrigation efficiency for the farmer will be when the present value of the net returns from water saving investments equals the additional costs of such investments. The net returns for water use efficiency are, in turn, determined by the crop price, the input costs, the risk and the management effort involved in growing and marketing the crop, and the physical limitations of the soil and climate (Gibbons, 1986). The higher the crop yield and price and the lower the cost of inputs, the larger will be the net returns from a prospective irrigation investment and the more likely it is that improvements in irrigation or water use efficiency are beneficial to irrigators.

3. Economic factors, irrigation water demand and efficiency

3.1. Value of irrigation water

The demand for water by an irrigator and its efficiency depends on its value in use. This is determined by the value of the marginal product of water: the physical yield from the application of an extra amount of water multiplied by the price received for the output. For most applications of water, the marginal product, although positive, will decline with each successive and extra application of water, so the demand for water by an individual irrigator will decline with the amount of water applied. The higher the marginal product from extra water usage, the greater the amount an irrigator will be prepared to pay for water (Hussain *et al.*, 2007). A profit maximizing irrigator will demand extra water up until the point that the value of the marginal product equals the price of acquiring the water.

In the case of irrigators watering perennial crops, such as citrus trees, the price paid for water may exceed the value of the marginal product of the water used in the current growing season if minimum watering is required to ensure the survival of plantations and future production. The high willingness to

pay reflects the situation of some irrigators who wish to maintain their plantations, or at least minimize the losses, to their fixed assets. This situation reflects the irrigators' objectives of both maintaining current profitability and reducing any future losses (Qureshi *et al.*, 2010a).

There is also a situation of 'asset fixity' where returns from the current use of an asset exceed its salvage value, but the current use returns are not sufficient to make additional investments profitable (Johnson, 1958). Asset fixity does not make irrigation economically inefficient but it can 'lock in' levels of irrigation efficiency for long periods of time based on the vintage of the capital assets. To the extent that increasing irrigation efficiency is a policy goal, asset fixity may be viewed as undesirable as it makes irrigators reluctant to restructure their capital assets. In particular, if the fixed investments (or assets) have not reached the end of their economic life, an irrigator may have limited economic incentive to respond to policy initiatives designed to increase irrigation efficiency. Thus, the vintage of past investments is a critical factor in determining the timing and extent to which policies, such as subsidies for water infrastructure, can generate water savings.

An important issue in terms of infrastructure investments that can generate water savings is the ability of irrigators to borrow. In particular, some farmers may be capital constrained in terms of how much they can borrow to upgrade their irrigation facilities; financial institutions may be reluctant to lend the capital needed to invest in infrastructure for higher irrigation efficiency to highly indebted farmers, even if the net present value of the investment is positive.

3.2. Risk and uncertainty in key parameters

Irrigators face uncertainties in term of the physical environment, commodity prices and escalating costs of production. To overcome uncertainty over water availability, irrigators may choose to hold a mixed portfolio of water entitlements based on their degree of supply reliability. Irrigators of annual low value crops may choose to use lower reliability water entitlements—called general security water—that have a lower price but also a lower probability of providing their full allocation in any given year. By contrast, perennial irrigators who must have water every year to ensure the survival of their vines or citrus may choose to hold more expensive high reliability water entitlements—called high security water—that has a high probability that it will receive at least some water or seasonal allocation even in low rainfall years.

Actual water deliveries or allocations are linked to total water available in the river system and are, generally, a fraction of the volumetric entitlements. Due to climate variability, this creates uncertainty for the farmers. On-going uncertainty over future water allocations may also deter irrigators from selling water and from entering into longer-term seasonal allocation contracts to hedge against any future reductions in their entitlements (Simmons, 2002; Peterson *et al.*, 2004). When facing stochastic plant–water needs and uncertain water supply, Willis & Whittlesey (1998) showed that risk-averse irrigators tend to over-use water relative to risk-neutral irrigators and, at the same time, under-estimate likely water supplies. These effects can lead to erroneous decisions and lost returns to investments.

The MDB is experiencing one of the most severe droughts observed recently in the world, driven by several years of rainfall deficit and record high temperatures, propagating water deficit throughout the hydrological cycle. The drought impedes investments in on-farm water savings—simply because there is no water—and triggers rather more immediate responses to meet the water needs. For instance, Zaman *et al.* (2005) summarized the annual temporary trade volume as a percentage of total irrigation deliveries for the Goulburn System in the Basin, and found that during the very wet years (1995–98) this percentage was in the range of 4–9% while in less wet years (1998–2001) it was 13–15%, and 18–23%

of irrigation deliveries in dry years (2001–03). This trend of an increase in the volumes traded in drier years arises from the fact that irrigators find it increasingly difficult to meet crop water demands in dry years and thus demand more water. In turn, this increases the quantity of water traded.

The extended drought in the Basin in recent years has also sharply increased groundwater use, as overall groundwater abstractions have not yet been capped. Estimated groundwater extraction in the MDB in 2004/05 was some 1,832 GL (CSIRO, 2008). This was more than twice since the surface water trading expanded in the mid-1990s. If the rate of increase seen in the last few years were to continue it would lead to use of about 2,100 GL per year by 2016/17 (Kirby *et al.*, 2006). Without any management intervention, by 2030, groundwater extraction could increase to 3956 GL/year (CSIRO, 2008). Evans (2004) has estimated that the growth in groundwater extractions reduced the surface water availability by as much as 2% per year over the period 1993–94 to 1999–2000, after the introduction of a surface water diversions cap. This is because rivers and groundwater in the MDB are connected and over extraction of groundwater has diminished the river flows (Khan *et al.*, 2008). In addition to reduced surface flows, excessive use of groundwater increases pumping costs and promotes infiltration of salts into groundwater systems, exacerbating risk and uncertainty.

3.3. Impact of water markets

Water markets provide incentives for the economically efficient allocation of water, compared to administrative allocative mechanisms (e.g., land-based water rights system), proactive strategies (e.g., promoting more efficient irrigation technologies) or reactive responses (e.g., compensatory schemes). Water markets (or water trading) require water rights to be clearly defined, and the mechanisms to facilitate and monitor trades must be established (Qureshi *et al.*, 2009). In Australia, since the introduction of water markets in the 1970s, the quantity of irrigation water used through markets has grown several times. As a consequence, annual permanent trade of entitlements is about 2% of the total volume of water traded, while total volume of seasonal allocations traded is about 10–20% of the allocations (Peterson *et al.*, 2004). Further economic gains are possible if barriers in water trading are removed and water is moved from lower to higher value uses (Peterson *et al.*, 2004; Qureshi *et al.*, 2007).

4. Water policy implications

Water reform in Australia is, in part, a response to climate variability and overuse by irrigation along with the decline in environmental flows. The efficacy of current water policy responses to these new pressure points remains unclear. In particular, decreasing inflows into catchments will be a major challenge in the MDB in the future. Current water reforms in the MDB attempt to address these challenges with 3.83×10^9 in grants and subsidies to increase irrigation efficiency and other measures, and 2.0×10^9 to buy back water from irrigators and reallocate it for the environment (Connell & Grafton, 2008). Implementing such reforms requires careful consideration of the differences between irrigation efficiency and economic efficiency, return flows and those factors that help determine the price and allocation of water, as well as socioeconomic and distributional effects across spatial, temporal and human scales (Molden *et al.*, 2010). For instance, less water for irrigation could have a major impact on the regional and national economies unless a significant effort is made to increase the value of water by maximising the efficiency of the current systems where possible, and by changing future water use

patterns (Keogh, 2007). Over-emphasis on benchmarking irrigation efficiency rather than market-based and cost-effective approaches can undermine the efficacy of the water reform process (Watson, 2007).

4.1. Irrigation subsidies, water purchases and cost effectiveness

Subsidies to farmers to increase irrigation efficiency reduce the marginal costs of water savings but do not, in general, change the expected gross returns. The economic justification for subsidies is that some of the water that is saved through water use efficiency improvements can be made available for the environment and other purposes (Madden *et al.*, 2007). The cost effectiveness of such an approach, however, depends on the share of the water savings allocated for public use and also the alternatives available (Keogh, 2007). For example, if the cost of subsidies to generate water savings for the environment exceeds the cost of purchasing water rights and allocating them for the environment, then savings through irrigation infrastructure subsidies are not cost effective.

Qureshi *et al.* (2010b) present the results of comparisons of expenditures on environmental flows under two different scenarios: (a) paying irrigators and water delivery firms to make capital and management investments that improve on-farm irrigation and water conveyance efficiency, with the saved water allocated to the environment; and (b) purchasing water from irrigators on the active MDB water market, with purchased water allocated to the environment. As shown in Figure 1, the least-cost option is Scenario B, and the total water supply attainable under an efficiency payment program is much less than by sourcing water on the market. The main reason for this result is that under the market
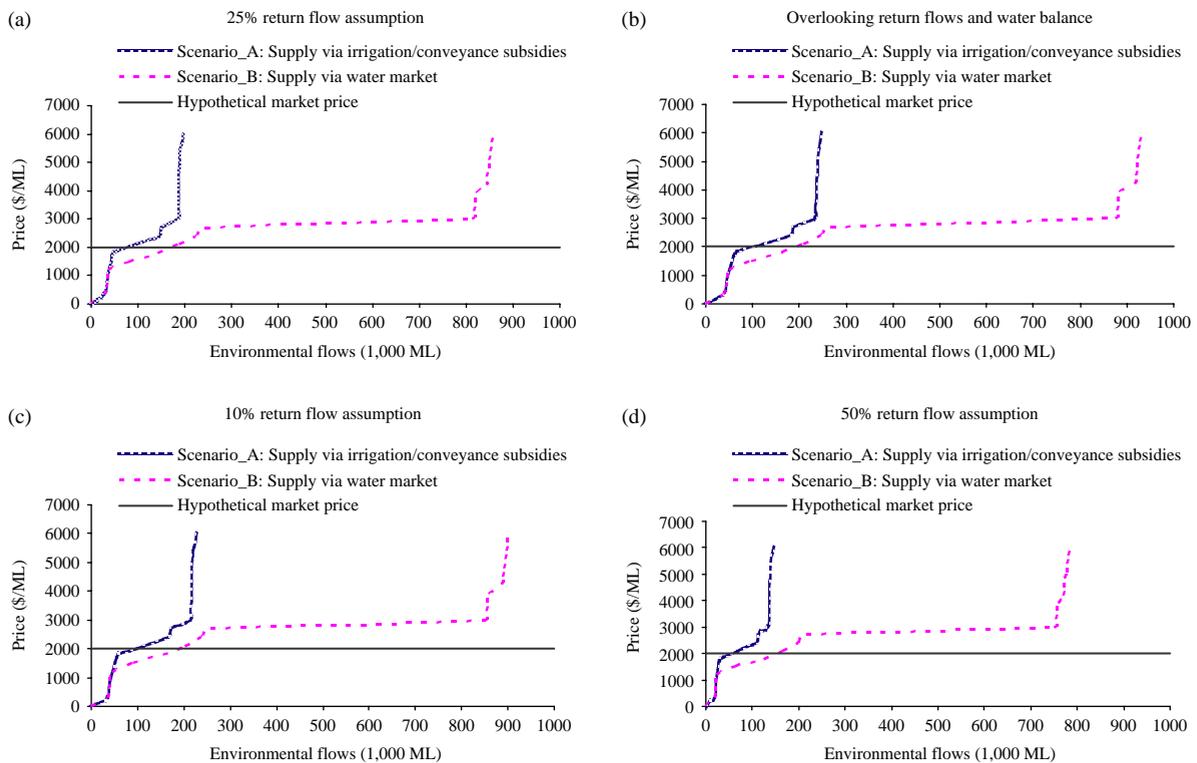

Fig. 1. Cost of environmental flows under alternative policies. (Source: Qureshi *et al.*, 2010b)

Scenario B, irrigators have more options to generate real water savings to sell the water to the government, than might be generated under an irrigation efficiency incentive payment policy alone in Scenario A.

Figure 1b shows that ignoring return flows can result in overestimation of the potential water savings and an underestimation of the costs incurred to generate those savings. Overlooking return flows might lead one to conclude that at a price of $2,700 per ML, about 188 GL of environmental flows could be generated under Scenario A. Yet, a comparison with Figure (1a) suggests that, when return flows are acknowledged, only about 150 GL of water will be supplied. Failure to account for return flows leads to an overestimate of water savings at the price of $2,700 by 33 GL (or 25%) and a substantial underestimate of the cost per unit, as it would take a unit price of around $5,100 to acquire 188 GL of water for the environment. This means that overall system water use efficiency which accounts for the return flows is greater than irrigation efficiency. Thus, improvements in irrigation efficiency do not translate into equal changes in system level efficiency.

Qureshi *et al.* (2010b) also considered upper and lower bounds of the water savings, on the assumptions of runoff and deep percolation flows contributing to return flows and system efficiency, so as to better understand the possible extent to which these programs may (or may not) generate additional environmental flows. As shown in Figure 1(c), when a small fraction (10%) of runoff and deep percolation becomes return flows, improvements in irrigation efficiency result in greater net additional water for the environment. By contrast, Figure 1d illustrates the cost-effectiveness of acquiring environmental flows when a large fraction (50%) of the runoff and deep percolation flows returns to the system.

The figures illustrate that higher irrigation efficiencies generate less water for environmental flows. The results suggest that the cost of supplying water for the environment would be 60% greater under a 50% rather than a 10% fraction of return flows. These results indicate that, when return flows are higher, more runoff and deep percolation stay within the catchment and the ability to generate environmental water flows through irrigation efficiency improvements diminishes. Qureshi *et al.* (2010b) even show that, should all the water savings be allocated to irrigators, it is even possible for overall net environmental flows acquired through that policy mechanism to decrease.

The marginal water savings from successive investments in infrastructure are also likely to decline with the amount invested due to diminishing returns. This is illustrated in Figure 2. On the vertical axis is the 'marginal return' in water savings on infrastructure investments measured in billions (i.e. 10^9) of litres of water not lost through evaporation or seepage, and that are generated from investments in irrigation delivery systems or on-farm water efficiency projects. On the horizontal axis is the amount spent on infrastructure investments to modernize irrigation. The relationship between water savings and the amount invested is downward sloping, reflecting the fact that initial investments generate the highest water savings and are likely to decline thereafter. So long as the expected return from water savings investments is more than the market price of water plus transactions costs, irrigators would undertake such investments without requiring government subsidies. The horizontal line in Figure 2 illustrates that alternative approaches such as buying water directly from irrigators or policies to promote different land-use practices will, at some stage, generate higher water savings than successive infrastructure investments.

Other policies designed to increase water savings will also be subject to diminishing returns. For instance, if governments purchase large quantities of water for the environment they are likely to increase its market price and may make further purchases more expensive on a per unit basis. The key point is that cost effectiveness in water reform requires that the marginal cost of generating a litre of
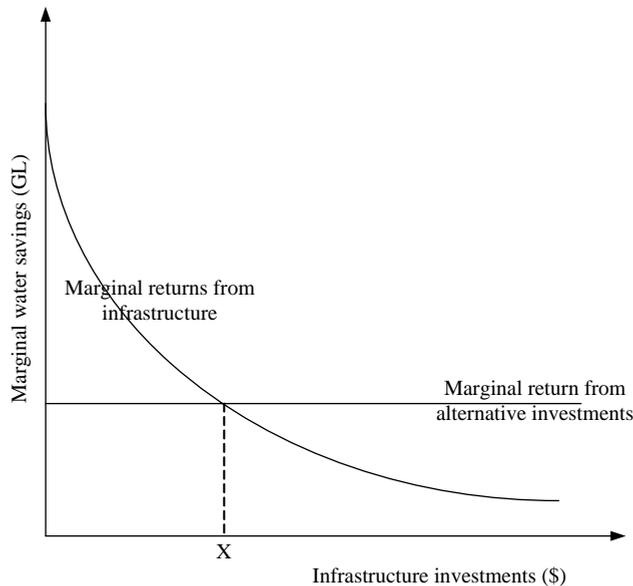
Fig. 2. Diminishing returns from water infrastructure investments.

water savings for the environment be equalized across all options, and the least cost alternatives should be adopted first.

4.2. Spatial and temporal issues

Differences in soil and climate types, and also the fixed nature of irrigation assets, mean that water diversions are not evenly distributed across a catchment. As a result, policies designed to increase environmental water allocation must account for where the water is purchased or where subsidies are paid in terms of maximizing the expected environmental benefits. For example, improved irrigation efficiency that increases downstream flows, all else being equal, to an environmental asset means less water is required downstream or more can be available for environmental assets upstream. Similarly, if environmental assets are downstream but very distant, then the evaporation of water savings may render few if any benefits to such assets. The key point is that for water reform to generate savings for the environment, the savings must be explicitly connected to the environmental assets which will benefit from increased water. Thus, when evaluating alternative investments (subsidies for irrigation efficiency or the purchase of water rights) the comparison should be between the expected environmental benefits generated versus the cost of the policy intervention. The higher the ratio, the more desirable the investment.

An important issue when facing the challenges of climate variability is how to respond to declines in rainfall and increases in evaporation in a timely fashion. Depending on the nature of the infrastructure investments, the water savings generated may take several years to materialize. When water entitlements are purchased, the ability to provide emergency water may also be delayed because, in low rainfall periods, the yields will also be lower but this can be partially offset by purchases of actual volumes of water (seasonal allocations) for the environment. When emergency base flows are needed to prevent irreversible environmental losses, considerations should be given to reconfigure rivers and water-dependent ecosystems (Young & McColl, 2009).

Meter inaccuracy is another source of losses, accounting for up to 25% of measured losses, compared to smaller amounts of water lost to evaporation (10%) and seepage or leakage (5%) (MJA, 2001). Losses can be reduced by fitting accurate meters, and by better monitoring and enforcement. These measures could represent a significant potential source of water savings for irrigation water providers. However, some forms of water loss in irrigation conveyance generate positive economic outcomes downstream (such as water used by other irrigators or available for non-consumptive use, such as for tourism or the environment) such that the net benefits from recovering water by increasing water use efficiencies may be less than that suggested by the raw data on measured losses (MJA, 2001).

5. Conclusions

Increasing water scarcity has generated an impetus for water reform in many countries, especially in terms of the trade-offs between agricultural water uses with the environment. To increase the amount of water available, Australian governments are undertaking a series of water reforms that include subsidies to farmers to increase irrigation efficiency, then using some of the water savings for the environment, and buying back of surface water entitlements to increase environmental flows.

Fundamental to effective water reforms is an understanding of the difference between irrigation and water-use efficiency, basin efficiency and economic efficiency. Increasing irrigation efficiency may, in some circumstances, reduce water for the environment and downstream users. Farmers who are economically efficient may not necessarily have the highest levels of irrigation efficiency. Further, a given water use that might be economically efficient for an individual farmer may not be economically efficient at a catchment or basin level, after accounting for the external cost imposed on others from its use.

The factors that determine the demand for irrigation water are also important in the water reform process and include the value of irrigation, the way irrigators manage risk and uncertainty, spatial and temporal factors, and the nature and impact of water markets across spatial and human scales. Supply side factors such as poor governance and institutional issues are often ignored as a cause of inefficient water use. By providing a clear understanding of these factors, and also differences in the various types of efficiency terms, a framework is provided for evaluating water reforms. This framework offers insights about how to overcome some of the key challenges of water scarcity and climate variability in arid and semi-arid environments.

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