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Opportunities for saving and reallocating agricultural water to alleviate water scarcity

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Abstract

As water scarcity worsens globally, there is growing interest in finding ways to reduce water consumption, and for reallocating water savings to other uses including environmental restoration. Because irrigated agriculture is responsible for more than 90% of all consumptive water use in water-scarce regions, much attention is being focused on opportunities to save water on irrigated farms. At the same time, many recent journal articles have expressed concern that claims of water-saving potential in irrigation systems lack technical credibility, or are at least exaggerated, due to failures to properly account for key elements of water budgets such as return flows. Critics have also asserted that opportunities for reallocating irrigation savings to other uses are limited because any freed up water is taken up by other farmers. A comprehensive literature and internet survey was undertaken to identify well-documented studies of water-saving strategies in irrigated agriculture, as well as case studies in which water savings have been successfully transferred to other uses. Our findings suggest that there is in fact considerable potential to reduce consumptive water use in irrigation systems when proper consideration is given to water budget accounting, and those savings can be beneficially reallocated to other purposes.

Keywords: Environmental flow; Irrigated agriculture; Irrigation efficiency; Water markets; Water reallocation; Water scarcity

Introduction

Water scarcity has been spreading and intensifying around the globe in recent decades, and is now estimated to be affecting water users and ecosystems dependent upon one-third of all rivers, lakes, and aquifers on our planet (Brauman *et al.*, 2016; Richter, 2016). Here we distinguish between natural

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aridity, in which available water supplies are limited due to relatively low volumes of precipitation and high levels of evapotranspiration, and the existence of scarcity, which results when the sum of consumptive human uses plus environmental water needs begins to approach or exceed the rate of water supply replenishment (United Nations, 2014).

Communities and businesses experience economic or social water scarcity when water supplies are insufficient to meet the demands being placed on them (Richter, 2016). Ecological water scarcity results when freshwater or estuarine ecosystems are depleted of the natural water flows necessary to sustain their species populations and ecological functions (Poff *et al*., 1997; Richter *et al*., 1997; Postel & Richter, 2003). Nearly one-half of all people and cities and three-quarters of all irrigated agriculture now face water shortage risks as available water supplies have become nearly or fully exhausted in water-scarce regions (Brauman *et al*., 2016), leading the World Economic Forum to identify water shortage crises as being among the top risks to the global economy (WEF, 2016).

Water scarcity and its impacts on people and nature ultimately represent a failure of water governance systems to constrain the consumptive use of water within the limits of sustainable water supply (Postel & Richter, 2003). This shortcoming of water governance is globally ubiquitous even though sustainability principles have been central to integrated water resource management frameworks for decades. These principles include recognition of the need to: ensure that every person has affordable access to clean drinking water; provide adequate water supplies for economically productive uses; and protect ecosystems dependent upon freshwater flows. For instance, recommendations adopted at the 2002 World Summit on Sustainable Development included the statement that ‘Integrated water resources management should be sustainable and optimize water security and human benefit per unit of water while protecting the integrity of ecosystems’ (United Nations, 2001). More recently, the Sustainable Development Goals, unanimously adopted in 2015 by the 193 member states of the United Nations, include a goal stating the intent to ‘Ensure access to water and sanitation for all’ (Goal #6; United Nations, 2015), along with the following commitments:

- By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes; and
- By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.

Despite this wide embrace of sustainability principles, very few governments have been able to successfully avert or lessen the frequency or intensity of water scarcity and shortages (e.g. Figure 1). This is also despite the fact that scarcity has been present in many societies and cultures for more than a century, and its damaging impacts on communities, economies, and ecosystems are well documented (Richter, 2016). Farmers in the Middle East, western Asia and western North America were exhausting many of their local water supplies by the turn of the 20th century. For example, when farmers of European descent first settled in the Gila River valley of central Arizona (USA) in the 1860s, they found extensive marshes and floodplain forests along the Gila River and its tributaries. Their diversions of water to grow water-intensive crops such as corn, barley, and wheat quickly dried the rivers and caused extensive ecological damage. Ironically, much of their irrigation systems had been reconstructed from more than 800 kilometres of irrigation canals originally dug by indigenous Hohokam people, who disappeared from the

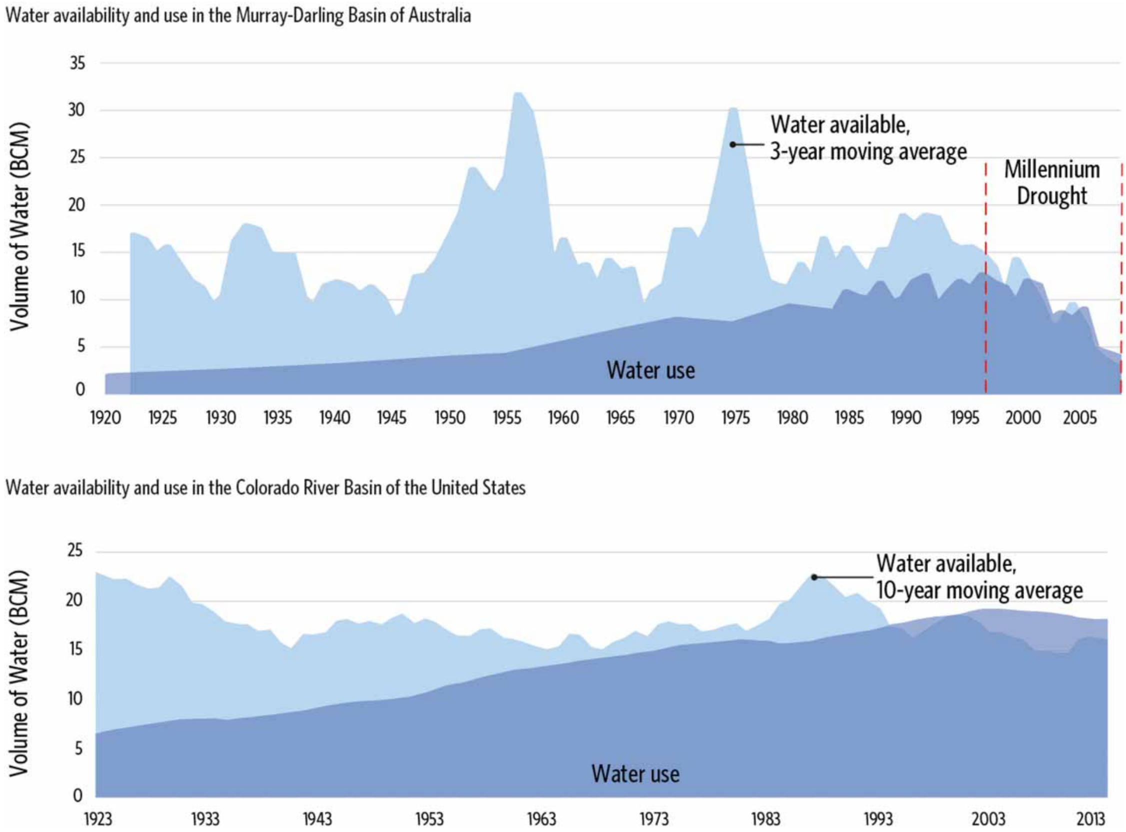

Fig. 1. Typical of rivers and aquifers in water-scarce regions around the globe, consumptive water use in the Murray-Darling Basin of Australia (upper graph) and the Colorado River Basin in the western United States (lower graph) increased gradually over time, eventually reaching and exceeding the limits of water availability. Note that the reduction in consumptive use seen in the Murray-Darling Basin after 1997 was due to the fact that water availability dropped sharply during the Millennium Drought of 1997–2009; by contrast, in the Colorado River Basin the use of stored water in large reservoirs, along with overdraft of groundwater aquifers in the basin, has enabled consumptive water use to exceed the river's supply during recent years (adapted from Richter, 2016; BCM = billion cubic metres, 10^9).

area around 1450 AD when an extended drought led to the collapse of their irrigated agricultural system (Richter *et al*., 2013).

For much of the past century, communities and governments facing water scarcity have placed heavy reliance on their ability to increase available supplies of water, rather than attempting to reduce demands. However, as discussed in Richter (2016), options for increasing water supplies are rapidly waning in many water-scarce regions, for three primary reasons: (1) there is no more surplus water to be found within reach of affordable water importation schemes; (2) the renewable water supply is in many places declining or becoming more variable due to climate change; and (3) the costs to secure more water, such as by using water storage reservoirs, water importation, desalination, or water reuse technologies, are too high. With diminishing opportunities for enhancing water supply, there is an urgent need to give demand management much greater emphasis in efforts to ameliorate water scarcity.

Many cities and even entire countries, such as the United States and Japan, have successfully stabilized their total water withdrawals in recent decades, even while their populations and economies have grown

(Richter, 2016). This curtailment of long-term trends of increasing water use has helped to prevent water scarcity from worsening in some regions. However, existing levels of consumptive water use and depletion of water sources remain precariously high in one-third of all water sources evaluated globally by Brauman *et al*. (2016), and in the 20% of aquifers assessed by Gleeson *et al*. (2012). Gaining relief from recurring water shortages in these depleted water basins will require concerted effort to reduce consumptive uses.

The greatest opportunities for reducing water consumption will likely be found in irrigated agriculture, where 90% of all consumptive use takes place (Hoekstra & Mekonnen, 2012; Brauman *et al*., 2016). Irrigation consumes 10 times more water than all other uses combined at the global level (Richter, 2014). As a consequence, there are few places in the world where water scarcity can be alleviated to any meaningful degree without substantially reducing the volume of water being consumptively used in agriculture. This does not necessarily imply the need to reduce agricultural production or revenue generation, however. This paper focuses on the potential water savings that might be realized in irrigated agriculture without loss of crop production, as well as opportunities to re-direct saved water toward environmental restoration or to other uses.

Reducing consumptive water use in irrigated agriculture

Considerable debate has arisen in recent years over the question of how much water – and even whether any water at all – can be realistically and practicably saved in irrigated agriculture, raising concern as to whether or not water-saving strategies in irrigated agriculture can be effectively deployed to alleviate water scarcity (see for example Lankford, 2006, 2012; Perry, 2007; Perry *et al*., 2009; Foster & Perry, 2010; Gleick *et al*., 2011; Scott *et al*., 2014). Much of this controversy is centered on two primary issues: the lack of proper water budget accounting in projects purporting to use less water for irrigation; and the feasibility of transferring any water savings to other water users or the environment.

Figure 2 illustrates the primary pathways of water flow into and through a farming area. When irrigation water is withdrawn from a water source and applied to farmland, some portion of the water is evaporated or taken up by crops as consumptive use, some percolates deep underground and becomes non-recoverable, and some portion subsequently returns to accessible surface or sub-surface water sources as *return flow*, where it may become available for reuse by others, or to support environmental flows. Accurate determination of potential water savings in irrigation requires estimation of the volume of water associated with each of the water flow pathways illustrated in Figure 2 so that the net change in '*water available for subsequent use'* (including environmental uses) can be properly evaluated (Lankford, 2006, 2012; Foster & Perry, 2010).

Unfortunately, until recently most water conservation efforts on farms, and claims of water-saving potential, have focused solely on changes in the volume of water withdrawn or applied to farm fields (large blue arrows in Figure 2), neglecting the volume and fate of return flow back into the original water source, creating misleading impressions of water benefits within the overall irrigation network within which water practices have been modified. This insufficient accounting can lead to counterintuitive outcomes, or a 'water efficiency paradox' (Scott *et al*., 2014), in which seemingly more efficient irrigation application can result in *greater* net consumptive use, ultimately lessening the volume available for subsequent use.

For example, many farmers have switched from flood (furrow) irrigation – thought to be highly wasteful because of the large volume of water applied to a farm field – to drip irrigation, which uses plastic

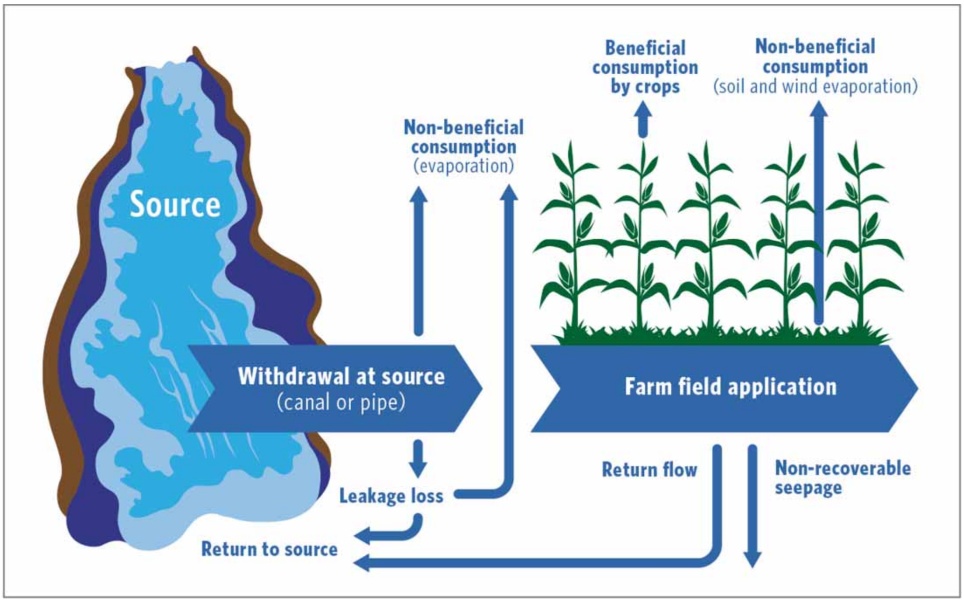

Fig. 2. The primary pathways of water flow in irrigated agriculture. Efforts to determine net water savings from investments in water conservation must account for the volumes of water represented by each of the arrows in this diagram.

tubing to place irrigation water directly at the base of the plants, thereby requiring a lesser overall volume of water to be applied, on a specific water duty basis, at the field scale of irrigated systems and farms. However, in many places much of the water thought to be wasted in flood irrigation returns to the original water source after application – via surface runoff or infiltration into shallow groundwater – and becomes available for other users, and thus, it is argued, is not truly 'wasted' (see return flow arrow in Figure 2). Paradoxically, when more efficient watering systems such as drip irrigation are installed, the new system may require lower volumes of water withdrawal and application to a farm field, but this reduced volume of withdrawal and farm application (i.e., *specific water use*, quantified as per hectare water application) can be more than offset by (1) lessened return flows to other users; plus (2) increases in consumptive crop use and productivity due to improved provision of water to the plants (see '*beneficial consumption by crops*' in Figure 2). This can result in a net reduction of overall water available to subsequent users and increased overall scarcity in the hydrologic system.

A second aspect of the debate relates to the question of whether or not any water savings can be realistically reallocated to other targeted uses, such as to improve environmental flows in a river, or conveyed downstream to urban users. In most accounts of purported water savings in irrigated agriculture, an alleviation of water scarcity is implied, but in the absence of any documentation about the fate of the saved water it is impossible to know whether water scarcity was lessened, or environmental flows improved (Lankford, 2013). In most real-world applications, any water left in water sources due to lessened water applications per hectare by farmers is consumptively used by other farmers sharing the same water source, either through increases in crop production on the same land area, by switching to a more valuable but consumptive crop (e.g. bananas), or by allowing the irrigated land area to expand (Organisation for Economic Co-operation and Development [OECD], 2015). For example, Scott *et al*. (2014) document that in both the Guadiana River basin of Spain and the Limari River basin of Chile, investments in irrigation efficiency from 1995 to 2007 – primarily converting flood irrigation to drip or sprinkler irrigation – substantially reduced the volume of water being applied to the original farm lands. These lessened withdrawals could have had the effect of restoring flows in these rivers, which are regularly dried completely from irrigation use. However, over ensuing decades the irrigated acreage in these basins was allowed to expand two-fold in the Limari and three-fold in the Guadiana. As a result, overall consumptive use increased substantially, worsening water scarcity in both basins.

Enabling increases in agricultural production is in many instances a highly desirable and intentional outcome of water-saving programs in irrigation farming. However, care must be taken to ensure that such programs do not make farmers more vulnerable to water shortages in the future by causing overall consumptive use to increase and increase vulnerability to scarcity in the future. For instance, a severe drought in the Limari basin of Chile during recent years has caused water availability to drop well below the volume needed to meet the consumptive demands that have doubled with expansion of irrigated acreage in the basin, and as a result, farmers have been forced to fallow more than 50% of the irrigated area in the past five years (Pablo Alvarez, Universidad de la Serena, personal communication).

Additionally, it should be explicitly acknowledged that by allowing consumptive water use to grow, river flows or groundwater levels will be further depleted, oftentimes to the point of complete drying, with attendant loss of biodiversity and social and economic benefits such as riverine fisheries. In the Limari, excessive drying of the lower section of the river has contributed to a steep decline in the population of freshwater shrimp (*Cryphiops caementarius*), adversely impacting the local fishing community (Morales & Meruane, 2013).

To assess the feasibility of saving and transferring water in irrigated agriculture, our research group performed a literature and internet review in an effort to identify well-documented field experiments and case studies.

Literature review of potential water savings in irrigated agriculture

Guided by the depiction of water flow pathways in Figure 2, our research group conducted a literature review for the purpose of identifying technically-credible case studies that could help document the water savings attainable by using various strategies or technologies, as described in Box 1. Our findings are summarized in Tables 1 and 2. For each reference reviewed, we evaluated the reduction in consumptive use and the potential increase in the volume of water that could be made available for subsequent use as a result of the strategy or measures applied in the study. In selecting references for inclusion in Tables 1 and 2, we filtered the studies we reviewed using the following questions:

1. Were the flow pathways illustrated in Figure 2 adequately and explicitly accounted for?
2. If all flow pathways were not explicitly accounted for, each of the following questions must be answered in the affirmative:
   (i) If the study documented a reduction in non-beneficial or beneficial consumptive use, could it reasonably be assumed that the water-saving measure applied could result in making an equal volume of water available for subsequent use in many settings?
   (ii) Did the study document, or could it reasonably be assumed, that crop yields would not be decreased (i.e., within 5% of original yield)?

Box 1. Descriptions of Water-Saving Measures.

No-till farming is a way of growing crops from year to year without disturbing the soil through tillage, thereby leaving crop residues in place. This has the benefit of increasing organic matter in the soil, leading to improved infiltration of precipitation or irrigation water. This practice can also reduce evaporation from the soil by lowering soil temperature due to shading, and reducing wind influences on evaporation.

Mulched ridges are used in furrow (flood) irrigation as a means for incorporating organic or other material into the ridges between tilled furrows, thereby providing many of the benefits described above for no-till farming.

Sprinkler irrigation is a method of applying irrigation water that is similar to natural rainfall. Water is distributed through a system of pipes, usually by using pumping to create pressure that forces water through the pipes. The irrigation water is then sprayed into the air through sprinklers. Various innovations in sprinkler equipment have been used to reduce the loss of irrigation water to evaporation, and to ensure that as much water reaches the plant roots as possible. These innovations include increasing the droplet size emerging from the sprinklers, placing the sprinkler heads close to the ground, changing the angle at which the sprinkler sprays water (i.e., 'low elevation spray application' or LESA), and using less pressure in the pipe system to avoid excessive spray (i.e., 'low energy precision application' or LEPA).

Drip irrigation refers to the slow application of low pressure water from plastic tubing placed near the plant's root zone, helping to reduce wind or soil evaporation. The plastic tubing can be placed on top of the ground surface, or it can be buried (sub-surface drip irrigation), thereby reducing or nearly eliminating surface evaporation and runoff.

Deficit irrigation is a watering strategy that can be applied using various types of irrigation methods. It involves the application of irrigation water at a rate or frequency lower than the crop's full water requirements. 'Regulated' deficit irrigation strategically manages the deficits at developmental stages when water stress will not impact yields negatively. Proper implementation of this strategy requires careful monitoring or modeling of plant stress and soil moisture.

Irrigation scheduling is similar in purpose to deficit irrigation, but does not involve intentionally stressing the plants. Instead, soil moisture – and in some instances, leaf water potential – is monitored to determine when the plant needs more water, thus avoiding application of water when it is not needed. Weather models are commonly used to estimate crop water requirements and optimize the timing and amounts of irrigation applications.

Irrigation timing is a form of irrigation scheduling, but focused on applying irrigation water at times when evaporation can be minimized, such as during night-time when temperatures and wind speeds may be lower.

***Alternate wetting and drying* (AWD)** is a watering strategy primarily applied to rice growing, as an alternative to continual flooding during planting and the growing season. AWD involves flooding the soil and then allowing the field to dry down before being re-flooded, thereby reducing the volume of water consumed.

Source water substitution involves use of an alternate source of water supply, for the purpose of avoiding overuse of traditional freshwater sources such as rivers, lakes, or aquifers. The most common substitute is recycled water, which is provided as wastewater from industries or domestic uses, and may be treated or not treated following the original use. Far less common in irrigated agriculture is the use of desalinated ocean water or salty groundwater.

Irrigation infrastructure improvement can take many forms, but in Table 1 it is used to refer to improvements in irrigation delivery systems. The most common approach is to line a previously unlined, earthen ditch with plastic or concrete to reduce soil infiltration and loss of water through canal leakage or weed transpiration. Less common is the conversion of an open canal to a piped system for the purpose of reducing both infiltration and surface evaporation.
Temporary or permanent fallowing involves the cessation of crop growing, on either a temporary (e.g., one-year) or permanent basis, for the purpose of reducing consumptive water use. In calculating potential reductions of consumptive use, the water consumed by intentional (i.e., revegetation) or accidental (i.e., weed growth) vegetative regrowth on the farm field must be accounted for.
Crop shifting involves the replacement of a more water-intensive crop with a crop requiring less water consumption. An important consideration is the change in revenue generated; in the ideal case, a lower-value water-intensive crop is replaced by a higher-value crop requiring less water consumption.
Vegetation management is undertaken to reduce undesirable plant growth and associated water consumption, such as the removal of weeds in farm fields or aquatic vegetation in irrigation storage reservoirs.

As an illustration of our evaluation of question 2i above, we found many studies involving infrastructure improvements in irrigation delivery systems, such as lining earthen canals with concrete or replacing ditches with pipes for the purpose of reducing leakage. However, very few of these studies addressed the fate of leaked water before the improvements were made, leaving open the question of whether the leaked water infiltrated into soils and became available for subsequent use, or was instead evaporated or taken up by weeds or other vegetation. The fact that these studies did not document return flows was not taken as a cause for rejecting the study, because it is reasonable to assume that in many settings, leaked water would not be recoverable for subsequent use, or could be returned to a river or other water source to support environmental benefits.

The water-saving potential of most of the measures listed in Tables 1 and 2 will vary with climatic region (e.g. evaporation potential) or with type of crop or other vegetation. Our objective was not to comprehensively project the volume or percentage of water savings that can be expected in every setting; instead, we have sought to illustrate the likelihood and the relative magnitudes of water-saving potential available using various types of strategies or technologies. We also did not attempt to quantitatively rank the ease, reliability, or cost of applying each of these measures due to very large differences in skills, labor costs, and economies across the geographies in which these measures could be applied.

However, our literature review did lead to a general conclusion that strategies for reducing beneficial consumptive use through crop management – i.e., by temporary fallowing or shifting to a new crop type – stand out in terms of reliability in water savings, and may be some of the easiest and cheapest strategies to pursue. It is also clear from our cursory review of crop prices and trends across many different regions that possibilities exist for farmers to shift to alternate crops, thereby saving substantial volumes of water while enabling them to sustain or even increase agricultural revenues (see Tables 2 and 3). For example, a shift from rice to cereal grains in the Murray-Darling Basin of Australia could be expected to earn 50% more revenue per unit of water consumed (Table 3) while at the same time consuming

Table 1. Water-saving measures in irrigated agriculture that can make more water available for other uses or environmental flow.

Water-Saving Measure	Primary Flow Pathway Estimated	Saved Volume	Water Savings %	Study Location	Citation
Soil Management					
No-till farming	Reduced non-beneficial consumption	900–1,250 m^3/ha/year	33–45%	Nebraska, USA	van Donk *et al.*, (2010)
No-till farming	Reduced non-beneficial consumption	1,020 m^3/ha/year	13%	California, USA	Mitchell *et al.*, (2012)
No-till farming	Reduced non-beneficial consumption	591 m^3/ha/year	48–54%	Kansas, USA	Klocke *et al.*, (2009)
Plastic-mulched ridges (furrow irrigation)	Reduced water application	1,500 m^3/ha/year	50%	Shaanxi Province, China	Wu *et al.*, (2015)
Irrigation Application					
Switch sprinkler to sub-surface drip	Reduced non-beneficial consumption	3,000 m^3/ha/year	20–25%	Kansas, USA	Lamm (2005)
Spray heads or low-angle impact sprinklers to LEPA sprinklers	Reduced non-beneficial consumption	15–33 m^3/ha/irrigation event	6–13%	Texas, USA	Schneider & Howell, (1993), cited in Lamm, (2005)
Switch from flood (furrow) to drip	Reduced water application	2,000–6,000 m^3/ha/year	40–46% at same crop yield	Anatolia Region, Turkey	Cetin & Bilgel, (2002)
Switch from flood (furrow) to drip	Reduced water application	3,035 m^3/ha/year	56%	Umerkot, Pakistan	Tagar *et al.*, (2012)
Switch from flood (furrow) to sub-surface drip	Reduced water application	1,070–3,180 m^3/ha/year	34–47%	Texas, USA	Enciso *et al.*, (2015)
Switch from flood (furrow) to sub-surface drip	Reduced water application	1,060–1,490 m^3/ha/year	32–57%	California, USA	Hanson *et al.*, (1997)
Regulated deficit irrigation (pistachios)	Reduced beneficial consumption and reduced water application	1,230 m^3/ha/year	33%	California, USA	Iniesta *et al.*, (2008)
Regulated deficit irrigation (almonds)	Reduced beneficial consumption and reduced water application	1,270 m^3/ha/year	14%	California, USA	Stewart *et al.*, (2011)
Regulated deficit irrigation (almonds)	Reduced beneficial consumption and reduced water application	1,820–3,112 m^3/ha/year	17–29%	California, USA	Goldhamer *et al.*, (2006)
Regulated deficit irrigation (grapefruit)	Reduced beneficial consumption and reduced water application	1,213–1,296 m^3/ha/year	28–60%	Adana, Turkey	Unlu *et al.*, (2014)

(*Continued.*)

Table 1. (*Continued.*)

Water-Saving Measure	Primary Flow Pathway Estimated	Saved Volume	Water Savings %	Study Location	Citation
Regulated deficit irrigation (strawberries)	Reduced beneficial consumption and reduced water application	2,289–2,315 m^3/ha/year	19–27%	Huelva Province, Spain	Lozano *et al.*, (2016)
Regulated deficit irrigation (quinoa)	Reduced beneficial consumption and reduced water application	650–1,400 m^3/ha/year	32–82%	Altiplano, Bolivia	Geerts *et al.*, (2008)
Regulated deficit irrigation w/mulching	Reduced water application	583 m^3/ha/year	76%	Shaanxi Province, China	Zhou *et al.*, (2011)
Alternate wetting and drying for rice	Reduced water application	1,429–2,461 m^3/ha/year	18–31%	Arkansas, USA	Linquist *et al.*, (2015)
Irrigation scheduling (soil moisture monitoring)	Reduced water application	1,390 m^3/ha each year	27%	Colorado, USA	Gleason, (2013)
Irrigation scheduling (soil moisture)	Reduced water application	1,036 m^3/ha/year	22%	Punjab, India	Perveen *et al.*, (2012)
Irrigation scheduling (soil moisture and leaf water potential monitoring)	Reduced beneficial consumption and reduced water application	819–1,600 m^3/ha/year	42–67%	Luancheng, China	Zhang, (2002)
Irrigation timing (daytime vs night-time)	Reduced non-beneficial consumption (evaporation)		12%	Salon de Provence, France	Molle *et al.*, (2012)
Source water substitution (using desalinated water)	Reduced withdrawal of water from source	10,370–25,340 m^3/ha/year	100%	Jordan Valley, Israel	Silber *et al.*, (2015)
Irrigation Infrastructure Improvements					
Canal lining, replacing canals w/pipes	Reduced non-beneficial consumption (evaporation)	48–1,494 m^3/year/metre of canal		Oregon, USA	Newton & Perle, (2006)
Crop Management					
Temporary fallowing of farm land	Reduced beneficial consumption	10,085 m^3/ha/year	100%	California, USA	Palo Verde Irrigation District, (2015)
Temporary fallowing of farm land	Reduced beneficial consumption	16,756 m^3/ha/year	100%	California, USA	Imperial Irrigation District, (2014a, 2014b)
Crop shifting (different combinations)	See Table 2				

(*Continued.*)

Table 1. (*Continued.*)

Water-Saving Measure	Primary Flow Pathway Estimated	Saved Volume	Water Savings %	Study Location	Citation
Other Vegetation Management					
Removal of invasive vegetation	Reduced non-beneficial consumption	2,000–4,000 m^3/ha/year savings versus native vegetation	~35%	New Mexico, USA	Weeks *et al.*, (1987)
Removal of invasive vegetation	Reduced non-beneficial consumption	25 m^3/ha/year savings versus native vegetation		Cape Province, South Africa	Dzikiti *et al.*, (2013)
Aquatic vegetation control	Reduced non-beneficial consumption	2,446 m^3/ha/year versus open water	27%	Nile Delta, Egypt	Rashed, (2014)
Aquatic vegetation control	Reduced non-beneficial consumption	1,300–4,500 m^3/ha/year versus open water	17–59%	Alabama, USA	Boyd, (1987)

Table 2. Opportunities to reduce consumptive water use through crop shifting.

Location	Season	Most-Intensive Crop	Required Water (m^3/ha)	Least-Intensive Crop	Required Water (m^3/ha)	Potential Water Savings from Substitution (%)	Source
Australia	2008–2009	Rice	14,100	Cereal crops not for grain, seed, or hay	2,200	84%	ABS, (2010)
New South Wales	2008–2009	Rice	14,100	Cereal crops not for grain, seed, or hay	1,900	87%	ABS, (2010)
Victoria	2008–2009	Fruit and nut trees	4,600	Cereal crops not for grain, seed, or hay	2,100	54%	ABS, (2010)
Queensland	2008–2009	Cotton	5,800	Cereal crops for hay	2,200	62%	ABS, (2010)
South Australia	2008–2009	Fruit and nut trees	7,300	Cereal crops for grain or seed	2,100	71%	ABS, (2010)
Western Australia	2008–2009	Nurseries, cut flowers, and cultivated turf	8,700	Grapevines	1,300	85%	ABS, (2010)
Tasmania	2008–2009	Vegetables	3,400	Grapevines	1,100	68%	ABS, (2010)
Northern Territory	2008–2009	Grapevines	8,400	Fruit and nut trees	2,700	68%	ABS, (2010)
Murray-Darling Basin	2008–2009	Rice	14,100	Cereal crops not for grain, seed, or hay	2,000	86%	ABS, (2010)
Egypt	Winter 2009–2011	Perennial clover	6,945	Fenugreek	2,930	58%	Dawoud, (2014)
Egypt	Summer 2009–2011	Sugar cane	22,793	Sunflower	5,952	74%	Dawoud, (2014)
California, USA	2013	Rice	13,716	Potatoes	5,181	62%	USDA, (2013)
Iowa, USA	2013	Potatoes	3,962	Tomatoes	609	85%	USDA, (2013)
Texas, USA	2013	Rice	7,010	Beans	1,524	78%	USDA, (2013)

Note: ABS = Australian Bureau of Statistics, USDA = United States Department of Agriculture.

Table 3. Comparison of water productivity for various crops, Australia and California.

Australia[a]		California[b]	
Crop Type	(AUD$/gigalitre of water)	Crop Type	USD$/acre-foot of water
Nurseries	15.5	Vegetables, horticulture	14,318
Vegetables	4.6	Cucurbits	6,343
Fruit & Nuts	2.9	Fresh tomatoes	5,621
Grapes	1.7	Fruits	3,281
Cotton	0.6	Vine grapes	3,129
Pasture (hay)	0.3	Onions, garlic	2,046
Cereals	0.3	Potatoes	2,046
Other broadacre crops	0.3	Almonds, pistachios	1,452
Rice	0.2	Cotton	692
		Sugar beets	685
		Grains	628
		Corn	609
		Rice	524
		Safflower	460
		Alfalfa	357
		Irrigated pasture	91

[a]Average of 2005–2008 data from Australian Bureau of Statistics, Gross Value of Irrigated Agricultural Production.
[b]Medellin-Azuara *et al.* (2015).

86% less water (Table 2). Even greater revenue and water-saving benefits could be realized from other crop-shifting transitions, particularly when converting to crops with very high water productivity. Such crop shifting will in many instances entail upfront capital costs in converting farm fields from one crop type to another, and may in some instances also require expenditures in new farm machinery or irrigation infrastructure to enable more efficient irrigation of the new crop type. However, such conversions can be expected to yield attractive revenue and water benefits in many cases.

Successful efforts to transfer saved water to other uses

Our research also revealed a large number of programs in which water savings in irrigated agriculture have been successfully re-allocated for environmental restoration or other uses (Table 4). Most of these transfers of saved water have been executed within the context of formal water rights systems, in which farmers have ceded their right to irrigate on either a temporary or permanent basis and sold some or all of their water rights to other water users or conservation interests. Three examples illustrate both the variety of actors involved in these transactions as well as funding sources that have enabled water transfers from irrigation to other uses. In each of these three cases, overall agricultural revenues have increased even while consumptive water use was reduced (more details are available in Richter, 2016).

- *San Diego County and Imperial Irrigation District, United States* – The San Diego County Water Authority has entered into an agreement with the Imperial Irrigation District that compensates farmers willing to temporarily fallow their farm land, or to implement other water-saving measures such as canal lining. The transfer of the saved water to San Diego County presently accounts for more

Table 4. Examples of programs that have transferred water savings to the environment or other users.

Program Name	Location	Year Started	Year Ended	Permanent or Temporary Transfers?	Total Volume Transferred (MCM)**	Original Water Use	New Water Use	Citation
United States								
Colorado Instream Flow Program	State of Colorado	1973	on-going	permanent	369	various	environmental flow	CWCB, (2016)
Colorado Instream Flow Program	State of Colorado	1973	on-going	temporary	71	various	environmental flow	CWCB, (2016)
Colorado Water Trust	State of Colorado	2001	on-going	both	23	primarily agricultural or municipal	environmental flow	Colorado Water Trust, (2016)
Columbia Basin Water Transaction Program	Columbia River Basin (many states)	2002	on-going	permanent	99	various	environmental flow	National Fish & Wildlife Foundation, (2016a)
Columbia Basin Water Transaction Program	Columbia River Basin (many states)	2002	on-going	temporary	1,300	various	environmental flow	National Fish & Wildlife Foundation, (2016a)
Great Basin Land and Water Trust, Truckee River Program	Truckee River Basin (states of Nevada, Utah, and California)	1998	on-going	permanent	10	irrigation	environmental flow	Great Basin Land & Water, (2016)
Idaho Water Transaction Program	Upper Salmon River Basin (State of Idaho)	2003	on-going	temporary	24	various	environmental flow	Idaho Department of Water Resources, (2016)
Imperial Irrigation District Quantification Settlement Agreement	Imperial Valley (State of California)	2003	on-going	temporary	1,479	irrigation	municipal	Imperial Irrigation District, (2014b)
Juniper Ridge Irrigation Hydroelectric Pipeline Project	Deschutes River Basin (State of Oregon)	2009	2010	permanent	18	canal leakage	environmental flow	LifeLast, (2016)

(*Continued.*)

Table 4. (*Continued.*)

Program Name	Location	Year Started	Year Ended	Permanent or Temporary Transfers?	Total Volume Transferred (MCM)**	Original Water Use	New Water Use	Citation
New Mexico Strategic Water Reserve	State of New Mexico	2005	on-going	temporary	6	various	environmental flow	New Mexico Interstate Stream Commission, (2015)
Palo Verde Irrigation District & Metropolitan Water District Agreement	State of California	2004	on-going	temporary	37	irrigation	municipal	Palo Verde Irrigation District, (2015)
Scott River Water Trust	Scott River Basin (State of California)	2007	on-going	temporary	4	irrigation	environmental flow	Scott River Water Trust, (2016)
Shasta Water Transactions Program	Shasta River Basin (State of California)	2012	on-going	temporary	7	Irrigation	Environmental flow	The Nature Conservancy, (2016)
Swalley Irrigation District Piping Project	Deschutes River Basin (State of Oregon)	2005	2007	permanent	3	irrigation	environmental flow	Aylward, (2013)
The Freshwater Trust's Flow Restoration Program	Deschutes River Basin (State of Oregon)	1996	on-going	permanent	29	irrigation	environmental flow	National Fish & Wildlife Foundation, (2016a)
Trans Pecos Water and Land Trust	Rio Grande river Basin (State of Texas)	2005	on-going	temporary	2	irrigation	environmental flow	Trans-Pecos Water & Land Trust, (2016)
Tumalo Irrigation District Bend Feed Canal Piping Project	State of Oregon	1999	2002	permanent	5	irrigation	environmental flow	Aylward, (2013)
Walker Basin Restoration	Walker Lake Basin (State of Nevada)	2010	on-going	permanent	22	irrigation	environmental flow	National Fish & Wildlife Foundation, (2016b)

(*Continued.*)

Table 4. (*Continued.*)

Program Name	Location	Year Started	Year Ended	Permanent or Temporary Transfers?	Total Volume Transferred (MCM)**	Original Water Use	New Water Use	Citation
Australia								
On-Farm Irrigation Efficiency Program, Rounds 1–3	Murray-Darling Basin (many states)	2010	2013	permanent	20	irrigation	environmental flow and irrigation	Cutting, (2013)
Private Irrigation Infrastructure Program for South Australia-Round 2	South Australia	2012	on-going	permanent	2	irrigation	environmental flow and irrigation	Cutting, (2013)
Murray-Darling Basin Balanced Water Fund	Murray-Darling Basin (multiple states)	2016	on-going	temporary	2 per year on average	irrigation	environmental watering of wetlands	Richter, (2016)
China								
Paddy Rice to Dryland Crop Project (PPRDC)	Miyun Reservoir, Chaobi River	2006	on-going	permanent	29	irrigation	municipal	Wu *et al.*, (2012)
Zhangye Water Reallocation	Heihe River Basin	2000	on-going	permanent	70	irrigation	industrial	Wang *et al.*, (2015)
Japan								
Agricultural Water Reorganization Measures (AWRM)	Tone River Basin	1968	2003	permanent	347	irrigation	municipal	Matsuno *et al.*, (2007)
Taiwan								
Changhwa and Yunlin Irrigation Association & Formosa Petrochemical Corporation	Taiwan	1997	2003	temporary	341	irrigation	industrial	Huang *et al.*, (2007)

Note: **MCM = million cubic metres, CWCB = Colorado Water Conservation Board.

than one-third of the water authority's supply, at a volume of more than 200 million cubic metres each year (Richter, 2016). Total compensation paid by the water authority to the irrigation district presently exceeds USD$60 million each year.

- *Murray-Darling Basin, Australia* – The Murray-Darling Basin Plan, adopted in 2012, calls for a consumptive use reduction of 2,750 million cubic metres, representing nearly 20% of water rights used for irrigation within the basin (Richter, 2014). The goals of this program include recovering water for the environment and enhancing overall water security. The Australian Commonwealth government has appropriated AUD$8.9 billion[1] for this purpose, with AUD$3.1 billion for direct purchase of water rights from farmers and another AUD$5.8 billion for implementation of water-saving measures on farms. As of June 2016, a total of 2,432 million cubic metres of water rights had been secured for the environment (Australian Government, 2016).

  To supplement these public efforts, The Nature Conservancy, a non-governmental conservation organization, in 2015 launched a Murray-Darling Basin Balanced Water Fund using private impact investment funds and philanthropic contributions to enable purchases of water rights from farmers (The Nature Conservancy, 2015). As of June 2016, 8.3 million cubic metres had been acquired by the fund. Twenty percent of the fund's water allocations will be dedicated to environmental purposes, on average.

- *Chaobai River Basin, China* – In response to a persistent decade-long drought that began in 1999 and the loss of more than half of its municipal reservoir storage capacity, the Beijing Municipal People's Government entered into an agreement with upstream farmers in the Chaobai River basin to shift from paddy rice irrigation to dryland crops (primarily corn), in an effort to increase water flows into Miyun Reservoir. Nearly 7,000 hectares were enrolled in the program, which has paid farmers 8,250 yuan (~USD$1244) per hectare per year, resulting in a net profit of more than 33% for farmers, and reduced their time spent in farming by 137 days per hectare (Wu *et al*., 2013). The project resulted in increased flows to the Miyun municipal reservoir of 29 million cubic metres per year.

Essential policies and regulations to enable successful water savings and transfers

The criticisms and skepticism of water savings in irrigated agriculture as reported in recent technical literature are well founded. However, our research group concluded that the inadequacies found in implementation and reporting of water savings are attributable to readily-identifiable shortcomings in water governance that can be addressed through reform in water policy and water-use regulations. Some of the specific enabling conditions and reporting requirements that will be essential to successful implementation include:

- *Establishing rights-based water allocation systems:* Abundant evidence from around the globe suggests that in the absence of a governance mechanism – such as issuance of surface water rights or well permits or other communal arrangements – to regulate allowable extractions, a water resource is likely to be depleted to exhaustion (Wada *et al*., 2012; Richter, 2014, 2016; OECD, 2015; Brauman *et al*., 2016).

[1] All references to billion in this paper represent 10^9.

The issuance of well-defined rights, supported by proper monitoring and enforcement, is also essential to the process of transferring water use rights to other users or the environment, and accounting for the cumulative consumptive use of a water source. It is particularly important to base the volume of the water right on allowable consumptive use – rather than on allowable withdrawal volumes – so that the net impact of the use on the hydrologic system can be readily ascertained. The total volume of consumptive use authorized through water rights should be explicitly tied to water availability, with consideration of the volume of water that needs to be left in freshwater ecosystems at any time to support their ecological health. The Australian system of issuing water entitlements – defining the maximum volume of water that could be consumed in a year by an entitlement holder – combined with a process for issuing seasonally- or annually-adjusted, percentage-based allocation shares (i.e., as x% of entitlement) – has proven very successful for this purpose (Richter, 2014; Young, 2015).

- *Capping consumptive water use*: Placing a limit on the total volume of water that can be consumed from each water source is an absolutely essential condition for success, as it enables governmental authorities or irrigation districts to prevent users from overusing a water resource (Richter, 2014, 2016). Such a cap can be constructed through limiting the total volume of rights or permits that are issued, but it should include a mechanism for adjusting consumptive use according to the seasonal or annual variability in water supply, as discussed in the bullet above. The implementation of a cap can be greatly aided by infrastructural mechanisms, such as control gates on irrigation canals, that enable regulators to limit, monitor, and enforce the allowable flow of water into an area.
- *Allowing for transfers of water-use rights*: The issuance of well-defined water rights not only enables regulation of total consumptive use in accordance with capped limits, but it also provides a means of accounting for transfers or trading of water-use rights among different users or sectors. Each of the water transfer programs listed in Table 4, and the three case studies highlighted in the previous section, are based upon the temporary or permanent trading of water-use rights. These transfers can be greatly aided by the establishment of a well-functioning water market, in which the holders of water-use rights can be incentivized to reduce their consumptive use because of their ability to sell the portion of their rights that is no longer needed (Debaere *et al*., 2014; Richter, 2016).

Summary and conclusions

Given that one-third of all freshwater sources on the planet are now being heavily depleted by excessive water consumption, and given that irrigated agriculture accounts for more than 90% of that consumption in water-scarce basins, it is absolutely essential to identify and implement strategies that can reduce consumptive irrigation use while maintaining agricultural production and livelihoods. Additionally, given the dire state of freshwater species and ecosystems in water-stressed regions, much of the saved water needs to be used to augment freshwater systems that have been excessively depleted.

Our research has documented reliable, credible ways to reduce consumptive water use in irrigated agriculture, and we have also identified many programs – both governmental and private – that have shown how to transfer water savings to other uses, including environmental restoration. However, success in these endeavors will require strict attention to proper water budget accounting in farm applications, as well as strong governance over water resources to reverse the pervasive trend of increasing depletion of the planet's freshwater sources.

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