frontiers in Environmental Science

PERSPECTIVE
published: 06 June 2018
doi: 10.3389/fenvs.2018.00048

The Contribution of Improvements in Irrigation Efficiency to Environmental Flows

*Conor Linstead**

WWF-UK, Living Planet Centre, Woking, United Kingdom

Increasing irrigation efficiency is often assumed to be a means of saving water and a route to increasing irrigated agricultural production or making water available for other purposes, such as communities, industry or ecosystems. There is a growing body of literature arguing that increasing irrigation efficiency does not reduce consumptive water use in agriculture, implying that no additional water is made available for supporting environmental flows. However, understanding the implications of changes in irrigation efficiency for environmental flows requires assessment at temporal and spatial scales between the daily to seasonal field level analysis of advocates for increasing irrigation efficiency to save water, and the annual basin scale view of some of its critics. When investigated at these intermediate temporal and spatial scales, there may be potential for improvements in irrigation efficiency to mitigate the effects of irrigation on flow timings to an ecologically meaningful extent. In situations where this is possible, in advance of implementing irrigation efficiency programmes, overall water consumption must be limited by an effective water allocation regime that explicitly recognises environmental flow needs in order to prevent expansion or intensification of irrigated agriculture. This paper sets out some of the key issues that practitioners working on environmental flows should consider in order to assess whether or not interventions to increase irrigation efficiency can support environmental flow objectives.

Keywords: irrigation efficiency, environmental flows, water saving, water allocation, sustinable agriculture

OPEN ACCESS

Edited by:
Rebecca E. Tharme,
Riverfutures Ltd, United Kingdom

Reviewed by:
Marloes L. Mul,
International Water Management Institute, Sri Lanka
Claudia Ringler,
International Food Policy Research Institute, United States
Nathanial Matthews,
Global Resilience Partnership, Sweden

****Correspondence:***
Conor Linstead
clinstead@wwf.org.uk

Specialty section:
This article was submitted to Freshwater Science, a section of the journal Frontiers in Environmental Science

Received: *14 December 2017*
Accepted: *22 May 2018*
Published: *06 June 2018*

Citation:
Linstead C (2018) The Contribution of Improvements in Irrigation Efficiency to Environmental Flows. Front. Environ. Sci. 6:48. doi: 10.3389/fenvs.2018.00048

INTRODUCTION

Freshwater ecosystems are in serious decline globally. The Freshwater Living Planet Index, an indicator of the abundance of populations of freshwater dependent species, has declined by 81% since 1970 (WWF, 2016). There are many reasons for this such as infrastructure, pollution, habitat loss or species exploitation (see Collen et al., 2014; Bunn, 2016), but one important reason in many basins is the diversion of water to irrigated agriculture. Globally, irrigated agriculture is the biggest user and consumer of water (Hoekstra and Mekonnen, 2012; Richter et al., 2017). Given the scale of its impact in some basins, therefore, efforts to address freshwater ecosystem decline by protecting or restoring environmental flows often focus on saving water in irrigated agriculture. This is a critical challenge given the importance of irrigated land for food production: 18% of the world's cropland is irrigated but it accounts for 40% of food production (Madramootoo and Fyles, 2010).

The term "environmental flows" is the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration, 2007). Irrigated agriculture affects each of the quality, quantity and timing components of environmental flows (Causapé et al., 2006; Kendy and Bredehoeft, 2006; Richter and Thomas, 2007; Poff and Zimmerman, 2010; Jägermeyr et al., 2017). The question of whether there are significant water savings to be made by improving irrigation efficiency is a contested one (Perry, 2007) but is of central importance when considering the dominant role of agriculture in total freshwater withdrawals globally, the projected increase in food demand (Tilman et al., 2011), and the deteriorating state of freshwater ecosystems (WWF, 2016). In addition, the influence of irrigation on the timing component of environmental flows, and changes as a result of increased efficiency, are important considerations.

This paper focuses on the interaction between water management in agriculture and environmental flows. Firstly, it looks at whether improvements in irrigation efficiency at a field scale can deliver water savings at basin scales, and therefore potentially contribute to the quantity component of environmental flows. Secondly, it looks specifically at the scope for delivering water savings by reducing non-beneficial evapotranspiration, because this is often a focus of water saving efforts where the limitations for basin-scale water savings of other efficiency improvement approaches are recognised. Thirdly, the key reasons for the differing perspectives on the issues under discussion are examined, as these must be understood by practitioners engaging in irrigated agriculture with an objective to support environmental flows. Finally, the paper examines whether, even in the absence of a contribution to the quantity component of environmental flows, increased irrigation efficiency can contribute to the timing component. The conclusions from the preceding discussion are drawn together to provide key considerations for practitioners engaging with irrigated agriculture to protect or restore environmental flows.

WATER SAVING AT BASIN SCALES FROM INCREASED IRRIGATION EFFICIENCY

Discourses on water saving in agriculture often focus on irrigation efficiency, with the assumption that, if efficiency is increased, more water will be available for expansion of agriculture, or water freed up for industry, communities or freshwater ecosystems. In this paper, "irrigation efficiency" is taken to mean the ratio of the amount of irrigation water consumed by the cropped area (beneficial and non-beneficial ET) to the amount of water supplied to the crop through irrigation (see Perry, 1999). With these broad aims in mind, programmes of irrigation modernisation and efficiency improvement are implemented by a range of actors from the private and public sectors, and non-governmental organisations (Batchelor et al., 2014). There is, however, a growing body of literature that contradicts the idea that water can be saved by increasing irrigation efficiency, rather it can lead to increased consumptive use of water (e.g., Ward and Pulido-Velazques, 2008; Batchelor et al., 2014; Pfeiffer and Lin, 2014; Scott et al., 2014; Kuper et al., 2017; Perry and Steduto, 2017). This is primarily because, in most circumstances, where irrigation water is applied in excess of that consumed as evaporation and transpiration it is returned to rivers (via surface or groundwater) or percolates to aquifers, and is therefore available for use elsewhere, by other users, or at another time. For example, Crosa et al. (2006) and Chen et al. (2003) found that more than 80 and 39.9% of the water in the Amu Darya and the Aksu River, China, respectively is irrigation return flow. Reductions in water applied to the field therefore, while they represent a saving to the farmer, do not equate to real water savings (i.e., reductions in the consumptive use of water) at larger scales. A major exception is where percolation of irrigation water beyond the root zone is going to an irrecoverable sink (e.g., a saline aquifer or water body) where reducing this flow does make additional water available for other uses (Batchelor et al., 2014).

Instead, programmes to increase irrigation efficiency can drive increases in water consumption for a number of reasons (Scott et al., 2014) indirectly related to the efficiency improvement interventions. Where water availability at the farm or irrigation scheme level remains unchanged, and land, labour and other inputs are available, irrigation efficiency improvements can free up water to extend the irrigated area, or grow more profitable crops, perhaps with a higher water requirement (Batchelor et al., 2014). Often, measures to increase irrigation efficiency give greater control of the timing and location of water distribution at a field level and contribute to increased yields. For a given crop variety, climatic conditions, and set of agricultural practices, there is a largely linear relationship between crop production (in kg) and transpiration (Perry and Steduto, 2017). Therefore, any increases in yield per unit area associated with improved irrigation efficiencies imply a proportionate increase in beneficial water consumption.

The outcome, therefore, of programmes to increase irrigation efficiency in a given area is likely to be increased consumptive use of water and reduced availability to other users and aquatic ecosystems downstream. Hu et al. (2017), for example, demonstrated the progressive reduction in the ratio of irrigation return flow to total applied water over the 1990s to 2010s from 0.5 to 0.23 in the Aksu River, as irrigation and cultivation practices developed and irrigation efficiency increased in the context of expanding irrigated agricultural area. Kuper et al. (2017) refer to aquifers and downstream water users as being the "silent victims" of programmes to promote irrigation efficiency. We can reasonably add rivers, wetlands and their freshwater ecosystems to this list.

WATER SAVING BY REDUCING NON-BENEFICIAL CONSUMPTION

In addition to improving irrigation efficiency by reducing percolation below the root zone, irrigation efficiency can be improved by addressing non-beneficial evaporation and transpiration (i.e., evaporation or transpiration from sources other than the crop). In cases where the limitations of increasing irrigation efficiency for saving water at the basin scale are recognised, attention is often turned to addressing non-beneficial consumption as this generally represent a significant fraction of overall field ET. This is done through techniques such as weed control, ground cover with crop residues and mulching, irrigation timing, reducing waterlogging, or the use of advanced irrigation techniques to reduce the wetted area (Batchelor et al., 2014; Richter et al., 2017). For example, mulching is often proposed as an effective means of reducing the fraction of water lost through non-beneficial soil evaporation. However, the evaporation and transpiration components of ET are interdependent (Villalobos and Fereres, 1990; Perry, 2011), interact in complex ways with the crop micro-climate, and cannot be considered in isolation. Under different crop and climate conditions, studies have found increases (Deng et al., 2006), decreases (Yan et al., 2015; cited in Li et al., 2008; Perry and Steduto, 2017), or very little change (van Donk et al., 2010; Balwinder-Singh et al., 2011) in overall ET, and both increases (van Donk et al., 2010; Balwinder-Singh et al., 2011; Yan et al., 2015), and decreases (Li et al., 2008) in crop yield as a result of mulching or use of crop residues to supress soil evaporation. Similarly, proponents of drip irrigation often point to the reduction in wetted area compared with flood irrigation as a proxy for reduced non-beneficial evaporation. However, this fails to account for the increased time the soil surface is wet under drip irrigation, in comparison with other methods (Perry, 2011; van der Kooij et al., 2013), and does not account for the effects of changes to the crop micro-climate on transpiration. The extent to which addressing non-beneficial evaporation and transpiration can provide savings in consumptive water use is, therefore, highly crop and context specific (Clemmens et al., 2008) and cannot be assumed.

ORIGINS OF THE DIFFERENT PERSPECTIVES ON IRRIGATION EFFICIENCY

In the context of drip irrigation, van der Kooij et al. (2013) suggest that incorrect interpretations of actual water savings often stem from a failure to properly quantify and account for the different components of the field water balance. In this review of studies looking at drip irrigation, van der Kooij et al. (2013, p. 106) found that water scarcity is the major justification for research on drip irrigation efficiencies but "none of the studies make explicit how the measured efficiency gains translate into wider water savings, or explain how these will help solving problems of water scarcity." In a comprehensive review of studies looking at the effects of introducing "hi-tech" irrigation Perry and Steduto (2017) found that very few studies document the effects in a way that allows for savings in ET to be estimated. Those that do are inconclusive or demonstrate increased water consumption.

In addition to quantification challenges of measuring transpiration and separating it from soil evaporation in the field (Steduto et al., 2012, p. 82), the lack of precise definitions of terms, and their inconsistent use across and within disciplines, is problematic (Seckler et al., 1996; Jensen, 2007; Perry, 2007; van der Kooij et al., 2013). The ambiguity in the terms used means that the interpretation of results in scientific literature can be dependent on the perspective of the reader, and is potentially incorrect (van der Kooij et al., 2013; Perry and Steduto, 2017). Much of the basis of the apparently contradictory views on water saving in irrigated agriculture derives from the differing perspectives of actors at different scales on who is saving water and for what: e.g., field level (farmer), irrigation scheme level (irrigation manager/engineer), catchment or basin level (water manager, hydrologist or ecologist).

Unambiguous use of terms and careful accounting for different components of water flow would greatly contribute to addressing the apparent dichotomy between proponents of increased irrigation efficiency as a means of saving water for other uses, and those that claim that there is no water saving benefit from improved efficiency.

RELEVANCE OF IRRIGATION EFFICIENCY FOR TIMING OF ENVIRONMENTAL FLOWS

From the perspective of environmental flows, although excess applied water in "inefficient" irrigation is not generally lost to the basin, the process of distribution through an irrigation scheme, percolation, and return to the river, does create a time delay on that flow: meaning that water might be withdrawn at the critical low flow period for ecosystems but returned, depending on the local context, perhaps some weeks or months later, at less ecologically critical times and spread over a longer period. Equally, withdrawing water from part of a catchment or basin and returning in another part might not affect the annual basin water balance but could be significant for particular river reaches or wetlands. Diverting water from such habitats may have significant ecosystem impacts even if no water is lost overall. In addition, the quality of irrigation return flows can be degraded due to agrochemicals or additional salt (e.g., Causapé et al., 2006; Kendy and Bredehoeft, 2006; Perry, 2011).

Kendy and Bredehoeft (2006) demonstrate the effect of irrigation efficiency on flow timings in the context of a Western US surface water irrigated system covering 2949 ha. The authors show that, in a modelling simulation where total crop water consumption remained constant, less efficient irrigation (50% efficient) depleted streamflow immediately downstream to a greater degree than more efficient irrigation (100% efficient) during the irrigation season. As the more efficient scenario is 100% efficient, there are no return flows and streamflow depletion only occurs during the irrigation season. Under the less efficient scenario the total consumptive loss and annual streamflow are the same as the more efficient scenario, but delayed return flows via groundwater augment non-irrigation season flows such that they are higher than the natural flow condition. The consequence of this is that the lowest flow month is shifted from February under natural conditions to August under both efficient and inefficient irrigation scenarios. However, maximum streamflow depletion in the irrigation season is significantly greater under the less efficient scenario. Venn et al.

(2004) report similar observations in terms of the effect of shifting to more efficient types of irrigation (flood to sprinkler) on seasonal flow timings in the Salt River Basin, USA. In a modelling simulation of an irrigation system in the Zarrineh Rud River, Iran, Ahmadzadeh et al. (2016) found no reduction in consumptive water use but changes to seasons flow timings as a result of a shift from surface to pressurised irrigation systems.

Irrespective of the degree of efficiency, therefore, irrigation has an impact on environmental flows through diversion of flows to consumptive agricultural use (Jägermeyr et al., 2017) and the operation of infrastructure such as dams and barrages (Richter and Thomas, 2007). While few studies have addressed explicitly the effects on flow timings of more efficient irrigation resulting from reduced withdrawals during irrigation seasons, Venn et al. (2004); Kendy and Bredehoeft (2006), and Ahmadzadeh et al. (2016) have done so and suggest that irrigation efficiency improvements can benefit environmental flow timings. This can occur both as the absence of an augmentation of non-irrigation season flows from slow (groundwater) return flows (which may be good or bad for environmental flows, depending on the wider catchment context) and reduced depletion of flows during the irrigation season. Clemmens et al. (2008) conclude that irrigation diversions that return to surface water systems change the timing of flows, which can be environmentally beneficial or non-beneficial, depending on the specific context. There is a clear need, however, for further research into this effect to enable generalised conclusions to be drawn as the available evidence is sparse. It should also be noted that realising the potential for ameliorating the impact of irrigation on river flows through increased irrigation efficiency is contingent on effective controls on withdrawals or allocations to prevent associated increases in consumptive use, as described above (Perry and Steduto, 2017).

CONCLUSION

Both those that promote irrigation efficiency at a field level and those that argue that this does not result in water saving at a basin scale over an annual cycle have valid points to make, but neither gives a complete picture for environmental flows. While both localised field or irrigation scheme perspectives, or water accounting approaches (e.g., Karimi et al., 2013) are essential for understanding the wider system context, neither the field scale and irrigation season perspective nor basin scale and annual water accounting perspective are sufficient for understanding the implications of promoting increases in irrigation efficiency for environmental flows. This requires consideration at multiple spatial and temporal scales, including at spatial scales between the field scale and the basin scale, and at temporal scales between irrigation application cycles and annual water budgets. Taking this multi-scale approach creates opportunities to optimise environmental flow gains at a landscape or basin scale using spatial targeting of interventions (e.g., Crossman et al., 2010).

Carried out in isolation, field level interventions to improve irrigation efficiency are unlikely to deliver improvements in environmental flows. There is little evidence of a significant potential for reducing consumptive water use at scale through field-focused programmes designed to improve irrigation efficiency. There is, however, some evidence that in some contexts there is scope for efficiency measures to mitigate the effects of large scale irrigation on flow timings.

Despite the complexities and knowledge gaps, for practitioners wanting to protect or restore environmental flows the preceding discussion points to some elements of a framework for engaging with irrigated agriculture:

A key first step should be to establish quantitatively (e.g., using modelling and field observations) whether, in the specific context being considered, there is potential for increased irrigation efficiency to deliver ecologically relevant improvements to the timing of flows. This assessment should consider the effects at multiple spatial scales (field, farm, irrigation scheme, sub-catchment, catchment, basin) and temporal scales (daily, monthly, seasonal, annual). Significant factors that need to be considered in this regard include, for example, operation of existing irrigation infrastructure, whether excess irrigation water is returned to rivers via surface (fast) or groundwater (slow) flow (Zeng and Cai, 2014), total consumptive water use in agriculture, the distance from the irrigated area to the river, geology, and lifecycles and habitat requirements of species. As discussed above, such assessments should also make use of unambiguous terms and definitions for the components of the water balance.

Where there is potential for improvements in irrigation efficiency to benefit environmental flow timings, interventions at a field level to increase irrigation efficiency must be preceded by the establishment of an effective water allocation system that prevents an associated increase in overall water consumption. Without an allocation regime in place before extensive irrigation efficiency improvements, the potential benefits are unlikely to be realised in the long term as consumptive use will increase through the mechanisms described above (Scott et al., 2014; Perry and Steduto, 2017; Richter et al., 2017).

Allocation schemes should explicitly account for environmental flows, rather than assuming that environmental flows can be delivered as the residual of improvements in irrigation efficiency (Batchelor et al., 2014). Allocations should also account for actual consumptive use and should be adaptable to changes over time in irrigation efficiency i.e., withdrawal or use allocations should decline as the prevailing irrigation efficiency increases to prevent overall increases in consumptive use. Or indeed, allocations can be reduced, with associated farmer support, in order to incentivise increased irrigation efficiency.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and approved it for publication.

REFERENCES

Ahmadzadeh, H., Morid, S., Delavar, M., and Srinivasan, R. (2016). Using the SWAT model to assess the impacts of changing irrigation from surface to pressurized systems on water productivity and water saving in the Zarrineh Rud catchment. *Agric. Water Manag.* 175, 15–28. doi: 10.1016/j.agwat.2015.10.026

Balwinder-Singh, Eberbach, P. L., Humphreys, E., and Kukal, S. S. (2011). The effect of rice straw mulch on evapotranspiration, transpiration and soil evaporation of irrigated wheat in Punjab, India. *Agric. Water Manage.* 98, 1847–1855. doi: 10.1016/j.agwat.2011.07.002

Batchelor, C., Reddy, V. R., Linstead, C., Dhar, M., Roy, S., and May, R. (2014). Do water-saving technologies improve environmental flows? *J. Hydrol.* 518, 140–149. doi: 10.1016/j.jhydrol.2013.11.063

Brisbane Declaration (2007). "The Brisbane Declaration: environmental flows are essential for freshwater ecosystem health and human well-being," in *10th International River Symposium*, 3–6 September 2007 (Brisbane, QLD).

Bunn, S. E. (2016). Grand challenge for the future of freshwater ecosystems. *Front. Environ. Sci.* 4:21. doi: 10.3389/fenvs.2016.00021

Causapé, J., Quílez, D., and Aragüés, R. (2006). Irrigation efficiency and quality of irrigation return flows in the Ebro River basin: an overview. *Environ. Monitor. Assess.* 117, 451–461. doi: 10.1007/s10661-006-0763-8

Chen, Y., Cui, W., Li, W., and Zhang, Y. (2003). Utilization of water resources and ecological protection in the Tarim River. *Acta Geogr. Sin.* 58, 215–222. doi: 10.11821/xb200302008

Clemmens, A. J., Allen, R. G., and Burt, C. M. (2008). Technical concepts related to conservation of irrigation and rainwater in agricultural systems. *Water Resour. Res.* 44:W00E03. doi: 10.1029/2007WR006095

Collen, B., Whitton, F., Dyer, E. E., Baillie, J. E., Cumberlidge, N., Darwall, W. R., et al. (2014). Global patterns of freshwater species diversity, threat and endemism. *Glob. Ecol. Biogeogr.* 23, 40–51. doi: 10.1111/geb.12096

Crosa, G., Froebrich, J., Nikolayenko, V., Stefani, F., Galli, P., and Calamari, D. (2006). Spatial and seasonal variations in the water quality of the Amu Darya River (Central Asia). *Water Res.* 40, 2237–2245. doi: 10.1016/j.watres.2006.04.004

Crossman, N. D., Connor, J. D., Bryan, B. A., Summers, D. M., and Ginnivan, J. (2010). Reconfiguring an irrigation landscape to improve provision of ecosystem services. *Ecol. Econom.* 69, 1031–1042. doi: 10.1016/j.ecolecon.2009.11.020

Deng, X.-P., Shan, L., Zhang, H., and Turner, N. C. (2006). Improving agricultural water use efficiency in arid and semiarid areas of China. *Agric. Water Manage.* 80, 23–40. doi: 10.1016/j.agwat.2005.07.021

Hoekstra, A. Y., and Mekonnen, M. M. (2012). The water footprint of humanity. *Proc. Natl. Acad. Sci. U.S.A.* 109, 3232–3237. doi: 10.1073/pnas.1109936109

Hu, Q., Yang, Y., Han, S., Yang, Y., Ai, Z., Wang, J., et al. (2017). Identifying changes in irrigation return flow with gradually intensified water-saving technology using HYDRUS for regional water resources management. *Agric. Water Manage.* 194, 33–47. doi: 10.1016/j.agwat.2017.08.023

Jägermeyr, J., Pastor, A., Biemans, H., and Gerten, D. (2017). Reconciling irrigated food production with environmental flows for sustainable development goals implementation. *Nat. Commun.* 8:15900. doi: 10.1038/ncomms15900

Jensen, M. E. (2007). Beyond irrigation efficiency. *Irrig. Sci.* 25, 233–245. doi: 10.1007/s00271-007-0060-5

Karimi, P., Bastiaanssen, W. G. M., and Molden, D. J. (2013). Water accounting plus (WA+) – a water accounting procedure for complex river basins based on satellite measurements. *Hydrol. Earth Syst. Sci.* 17, 2459–2472. doi: 10.5194/hess-17-2459-2013

Kendy, E., and Bredehoeft, J. D. (2006). Transient effects of groundwater pumping and surface-water-irrigation returns on streamflow. *Water Resour. Res.* 42:W08415. doi: 10.1029/2005WR004792

Kuper, M., Ameur, F., and Hammani, A. (2017). "Unraveling the enduring paradox of increased pressure on groundwater through efficient drip irrigation," in *Drip Irrigation for Agriculture: Untold Stories of Efficiency, Innovation and Development,* eds J. P. Venot, M. Kuper, M. Zwarteveen (Abingdon: Routledge), 85–104.

Li, Q. Q., Chen, Y. H., Liu, M. Y., Zhou, X. B., Yu, S. L., and Dong, B. D. (2008). Effects of irrigation and straw mulching on microclimate characteristics and water use efficiency of winter wheat in North China. *Plant Prod. Sci.* 11, 161–170. doi: 10.1626/pps.11.161

Madramootoo, C. A., and Fyles, H. (2010). Irrigation in the context of today's global food crisis. *Irrig. Drain.* 59, 40–52. doi: 10.1002/ird.555

Perry, C. J. (1999). The IWMI water resources paradigm – definitions and implications. *Agric. Water Manage.* 40, 45–50. doi: 10.1016/S0378-3774(98)00102-4

Perry, C. (2007). Efficient irrigation; inefficient communication; flawed recommendations. *Irrig. Drain.* 56, 367–378. doi: 10.1002/ird.323

Perry, C. (2011). Accounting for water use: terminology and implications for saving water and increasing production. *Agric. Water Manage.* 98, 1840–1846. doi: 10.1016/j.agwat.2010.10.002

Perry, C., and Steduto, P. (2017). *Does Improved Irrigation Technology Save Water? A Review of the Evidence*. Cairo: Food and Agriculture Organization of the United Nations.

Pfeiffer, L., and Lin, C.-Y. (2014). Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. *J. Environ. Econom. Manage.* 67, 189–208. doi: 10.1016/j.jeem.2013.12.002

Poff, N. L., and Zimmerman, J. K. H. (2010). Ecological responses to altered flow regimes:a literature review to inform the science and management of environmental flows. *Freshwater Biol.* 55, 194–205. doi: 10.1111/j.1365-2427.2009.02272.x

Richter, B. D., Brown, J. D., DiBenedetto, R., Gorsky, A., Keenan, E., Madray, C., et al. (2017). Opportunities for saving and reallocating agricultural water to alleviate water scarcity. *Water Policy* 19, 886–907. doi: 10.2166/wp.2017.143

Richter, B. D., and Thomas, G. A. (2007). Restoring environmental flows by modifying dam operations. *Ecol. Soc.* 12:12. doi: 10.5751/ES-02014-120112

Scott, C. A., Vicuña, S., Blanco-Gutiérrez, I., Meza, F., and Varela-Ortega, C. (2014). Irrigation efficiency and water-policy implications for river basin resilience. *Hydrol. Earth Syst. Sci.* 18, 1339–1348. doi: 10.5194/hess-18-1339-2014

Seckler, D., Amarasinghe, U., Molden, D., de Silva, R., and Barker, R. (1996). *The New Era of Water Resources Management From "Dry" to "Wet" Savings*. IIMI Research Report5, IIMI, Colombo.

Steduto, P., Hsiao, T. C., Fereres, E., and Raes, D. (2012). *Crop Yield Response to Water*. Rome: FAO.

Tilman, D., C., Balzer, J., Hill, J., and, B. L., Befort (2011). Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. U.S.A.* 108, 20260–20264. doi: 10.1073/pnas.1116437108

van der Kooij, S., Zwarteveen, M., Boesveld, H., and Kuper, M. (2013). The efficiency of drip irrigation unpacked. *Agric. Water Manag.* 123, 103–110. doi: 10.1016/j.agwat.2013.03.014

van Donk, S. J., Martin, D. L., Irmak, S., Melvin, S. R., Petersen, J. L., et al. (2010). Crop residue cover effects on evaporation, soil water content, and yield of deficit-irrigated corn in west-central Nebraska. *West Central Res. Extension Center North Platte*. 53, 1787–1797. doi: 10.13031/2013.35805

Venn, B., Johnson, D., and Pochop, L. (2004). Hydrologic impacts due to changes in conveyance and conversion from flood to sprinkler irrigation practices. *J. Irrig. Drain. Eng.* 130, 192–200. doi: 10.1061/(ASCE)0733-9437(2004)130:3(192)

Villalobos, F. J., and Fereres, E. (1990). Evaporation measurements beneath corn, cotton, and sunflower canopies. *Agron. J.* 82, 1153–1159. doi: 10.2134/agronj1990.00021962008200060026x

Ward, F. A., and Pulido-Velazques, M. (2008). Water conservation in irrigation canincrease water use. *Proc. Natl. Acad Sci. U.S.A.* 105, 18215–18220. doi: 10.1073/pnas.0805554105

WWF (2016). *Living Planet Report 2016. Risk and Resilience in a New Era*. Gland: WWF International.

Yan, N., Wu, B., Perry, C., and Zeng, H. (2015). Assessing potential water savings in agriculture on the Hai Basin plain, China. *Agric. Water Manage.* 154, 11–19. doi: 10.1016/j.agwat.2015.02.003

Zeng, R., and Cai, X. (2014). Analyzing streamflow changes: irrigation-enhanced interaction between aquifer and streamflow in the Republican River basin. *Hydrol. Earth Syst. Sci*. 18, 493–502. doi: 10.5194/hess-18-493-2014

Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.