

A CHARTER FOR FLEXIBLE FRUGAL FLOURISHING IRRIGATION IN A WARMING WORLD

UNE CHARTE POUR UNE IRRIGATION SOUPLE, ECONOMIQUE ET PROSPERE DANS UN MONDE EN RECHAUFFEMENT

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ABSTRACT

The paper proposes a Charter for flexible frugal flourishing irrigation in a pressure-pot warming world. Via this Charter, the paper explores the future of irrigation management and governance. By 'pressure-pot warming world', irrigation will have to deliver more food from less water because it faces a more dynamic, hotter world with stiffer water competition. By 'flexible', irrigation will have to be better suited to changes in water availability in a dynamic climate – both dryness and wetness. By 'frugal', irrigation will have to consume less water per hectare, system and catchment when needed. By 'flourishing', irrigation should protect or boost crop production and other water uses and benefits over the baseline of many of today's irrigation systems. To meet and succeed in this challenging environment, irrigation needs a better understanding and management of water control. In simple terms, water control is the ability to hold, direct, place and apportion water over time and space across different scales. Refining this definition, the paper proposes 'integrated irrigation water control'. Building on this definition, the Charter is presented as a framework with four main parts; 1) context, 2) aim and 8-axis definition of water control; 3) 10 principles, and 4) researched and applied types and pathways of irrigated systems. Positing this Charter, the paper brings additional detail on irrigation and blue water depletion debates.

Keywords: irrigation management and governance; water availability; irrigation needs; catchment; irrigated systems.

RESUME

L'article propose une Charte pour une irrigation souple, économe et prospère adaptée à un monde qui se réchauffe et subit des pressions croissantes. A travers de cette Charte, l'article explore l'avenir de la gestion et de la gouvernance de l'irrigation. En «réchauffant le monde par des marmites à pression», l'irrigation devra produire plus d'alimentation avec moins d'eau, face à un monde plus dynamique et plus chaud avec une concurrence hydrique plus forte. Le terme «souple» implique que l'irrigation devra mieux adaptée aux changements de la disponibilité de l'eau dans un climat dynamique – à la fois sécheresse et humidité. Le terme «économe» indique que l'irrigation devra consommer moins d'eau par hectare, par système et par bassin versant lorsqu'il sera nécessaire. Le terme «prospère» constate que l'irrigation devrait protéger ou stimuler la production agricole et d'autres utilisations et avantages de l'eau par rapport à la base de nombreux systèmes d'irrigation actuels. Pour relever le défi d'environnement difficile, l'irrigation exige une meilleure compréhension et gestion du contrôle de l'eau. En termes simples, le contrôle de l'eau est la capacité à retenir, diriger, placer et répartir l'eau dans le temps et dans l'espace, à différentes échelles. En affinant cette définition, l'article propose une gestion intégrée de l'eau d'irrigation». S'appuyant sur cette définition, la Charte est présentée comme un cadre composé de quatre parties principales : 1) le contexte, 2) l'objectif et 8 axes de définition de la gestion de l'eau; 3) 10 principes, et 4) types et voies de systèmes irrigués étudiés et appliqués. En présentant cette charte, l'article apporte des détails supplémentaires sur les débats relatifs à l'irrigation et à l'épuisement des ressources en «eau bleue».

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Mots-clés : Gestion et gouvernance de l'irrigation; Disponibilité de l'eau; Besoins en irrigation; Bassin versant; Systèmes irrigués.

INTRODUCTION

There are ongoing concerns about the productivity and resilience of irrigated agriculture as it faces a warming world brought about by climate change (Onyeaka et al., 2024; Ward, 2022). For example, IWMI is working on a Global Commission to address water for food. The World Bank has just launched its Nourish and Flourish (N&F) framework which recognises the challenges of delivering sustainable irrigation in a world facing rapid environmental change (Talbi et al., 2026).

This Charter tries to bring additional irrigation detail to these debates and take issue with some of the consensus contained in those publications. For example, the World Bank N&F report treats irrigation on a continuum with rainfed agriculture. This basic introductory framing is insufficient for today's problems and will allow irrigation to escape close attention. In another example, the draft World Water Congress Marrakech declaration on "Water in a Changing World: Adaptation and Innovation" makes no mention of irrigation. Furthermore, this charter goes beyond framing irrigation as climate-smart which too often sees the need for precision field irrigation delivered by micro/drip/IoT/computer technologies and packages (Obaideen et al., 2022).

The Charter in this paper omits much, but it highlights a need for change. If 'business as usual' continues (water remains poorly controlled), irrigation will keep colonising freshwater, remain upstream of other sectors, be treated as the act of watering fields (Lankford & Agol, 2024), or be researched in an uncoordinated hobbyist fashion. Without a more-systematic approach to water control and irrigation, the sector will not be well placed to face a warming, climate-turbulent, water-competing world whilst maintaining a key role in growing food and fibre, supporting livelihoods, consuming less water and carbon-based energy – and/or banking more water in storage or for nature. Genuinely tough choices lie ahead.

THE CHARTER FRAMEWORK

Illustrated in Figure 1, the Charter is presented via a framework with four main parts; 1) context, 2) aim and 8-axis definition of water control; 3) 10 principles, and 4) researched and applied types and pathways of irrigated systems.



Figure 1. A charter for flexible frugal flourishing irrigation in a warming world

Context, trends and fit

For the context, trends and fit of irrigation, please see the bullet points at the top of the Fig 1. These points say irrigation is already facing and adapting to many pressures and constraints that will escalate in the future – especially during extended and severe drought periods. This future indubitably means irrigation's accountability and performance will have to improve. Either this change will be exogenously forced (e.g. by droughts and less water) or change will come pro-actively from the world's water, agriculture and irrigation farmers, managers, researchers and institutes. The context is part of the framework; analysis is needed to determine how and why current irrigated systems fit with, and are prepared for, existing and new water governance regimes.

Integrated irrigation water control (IIWC)

Irrigation in a pressure-pot warming world will have to respond to mounting pressures by improving water control. This requires a future-facing definition of water control, not one allied to current irrigation or simple conceptions of irrigation. Therefore, 'integrated irrigation water control' (IIWC) is defined as "the regularly assessed flexible careful management and apportionment of irrigation water abundance and scarcity to meet crop and other water demands throughout the scales and time periods of an irrigated system, facilitated by the purposive design, operation and maintenance of irrigated and associated green infrastructure, in order to manage, match, and benefit from dynamic multiple water supplies, whilst accommodating variable and uncertain hydrological, environmental, social, political and engineering factors".

IIWC is characterised via eight two-way axes (Figure 2). Each of the two-way axes portrays irrigation systems as a balance between different priority property. If the system is at one end of the axes, this property predominantly features. Most systems will sit as hybrids somewhere between the ends of the axes. All 8 axes apply to within the irrigated system boundary, and its effects on its periphery (neighbours) and the next scale up. The eight axes ask whether:-

1. Water is distributed by sharing out available supply (top down) or by aiming to meet crop water demand (bottom-up)
2. Water is conveyed and distributed by channels or pressurised pipes, or both
3. Water is distributed using human observations and dialogue, or is controlled by sensors computers and actuators
4. Water distribution is guided by observations or simple/ no metrics (such as days, on/off, rudimentary water levels) or is guided by very clear knowledge of water duties/hydromodules in litres per second per hectare
5. The physical design of the water distribution is not tight (it is lax) or it is carefully dimensioned to apportion water to fit peak water demand periods
6. Sources for irrigation water overlap and are numerous (e.g. soils, rainwater harvesting, wastewater, groundwater), or are few (e.g. surface water only) drawn from one abstraction point
7. Green infrastructure (e.g. soils, ponds, hollows) is used to retain and slow down rainfall and runoff during periods of abundance, or is not found because the system has prioritised clean grey infrastructure (e.g. levelled fields)
8. The irrigation hardware is minimally able to alter irrigation schedules for irrigating mixed cropping (and off-peak periods) or it can be flexible. (On larger systems this axis might involve trade-offs for water control at peak periods; note rigid systems can adjust during non-peak periods but flexible systems might struggle to schedule tightly during peak periods).

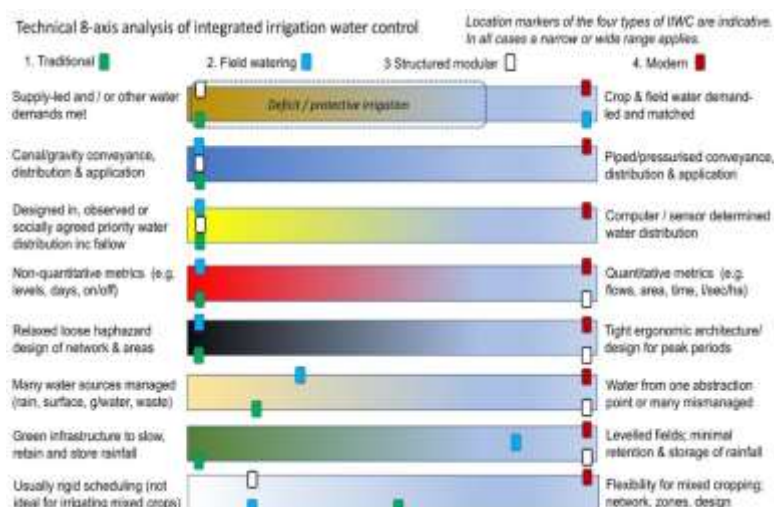


Figure 2. An eight-axis characterisation of integrated irrigation water control

At this stage, the axes do not predetermine levels and metrics of control and efficiency – rather they invite qualitative analysis and dialogue. Water supplies covered by IIRC include surface and groundwater flows, rain, soil, stored, and recycled wastewater – plus their management in order to benefit from periods of abundance. Water demands covered by IIRC include crops at different stages of growth, and other priority needs such as domestic and ecological provisioning. This definition of water control accommodates both demand and supply management, periods of abundance and scarcity, and the need for regular dialogue amongst irrigation's user and stakeholders. Working across all the axes involves overlaps and trade-offs – for example tight irrigation control may preclude the widespread application of green infrastructure to slow down rainfall-runoff.

The charter's 10 principles

Through 10 interlinked principles, the Charter reflects on how irrigated systems might deliver, or benefit from, integrated irrigation water control, and therefore prepare for a more unpredictable, dynamic and hotter world. Briefly these 10 principles are:-

- **Water, land and people will have to become sustainable within a dynamic range.** Integrated irrigation water control ensures that on average irrigation systems fit their catchment and aquifer context – hydrologically, legally and institutionally. This sustainability principle (Rosa, 2022) brings to the fore the need to use accurate water control to bear down on aggregate water depletion (whilst sustaining crop growth) so that field- and system-scale reductions in applied water are converted to real water savings. There is considerable misunderstanding about the hydrology of real water savings (Lankford, 2023) which will need addressing (see points 3 and 8 below).
- **A non-equilibrium and resilience approach to irrigated systems to fit climate variability.** Enhanced water control is needed to successfully cope with dynamic or non-equilibrium climate and weather (Lankford & Beale, 2007). This should allow irrigation (e.g. land, withdrawals, duration) to purposively contract and expand to match forecasted periods of aridity or wetness. This will require better prediction of climate (# 6 below), and a matching of irrigation demand to a changing 2-3 month supply window. This treats drought as 'shock-learning' to lock in lessons for the long run. Note, non-equilibrium irrigated resilience is not the same as irrigation sustainability but it is connected to sustainability in the long run. For example, either irrigated systems use drought to ratchet up aggregate water consumption over time becoming unsustainable in non-drought periods and less resilient to future drought (Lankford et al., 2023). Or we encourage systems to find a sustainable ceiling of aggregate water consumption in non-drought periods in order to provide water for other sectors and store excess water ready for the next drought, thereby enhancing drought resilience.

- **Multi-factor irrigation efficiency, productivity, allocation and banking.** It is too easy to promote irrigation efficiency as climate-smart without it being well understood (Lankford et al., 2020). Thus the Charter's starting point is water control (and then efficiency) utilised for a number of purposes. 1) Water control, for irrigation scheduling for crops (and often for other uses such as domestic supply) across space and time, will have to become more accurate. Furthermore, water control across the scales and periods of an irrigated system (from crop level to catchment, and from early to mature crop growth) will have to involve minimal or effective monitoring. 2) Water control will enable more widespread deployment of deficit, protective or alternate wet-and-dry (AWD) irrigation which both needs and encourages good water control. 3) Water control manages the paracommons which asks; who gets the gain of reduced consumption (or who loses from efficiency gains?) (Lankford & Scott, 2023). The paracommons envisage four parties compete over these savings; the proprietor making the savings, an immediate neighbour, society, or nature. A fifth option banks the gains in storage ready for later use by one or all of the four parties. 4) How water control and higher levels of efficiency are achieved by the four different types of irrigation systems is discussed in the four pathways below. 5) To facilitate careful water management, water control and efficiency will need robust but easy to understand indicators. One option is via the indicator Days to Day Zero.
- **Multi-scale 'designed-in' architecture of technologies and tools.** Delivering integrated irrigation water control should not be onerous. We need to consider how to make irrigation systems easier to run at higher levels of performance. Usually the solution is automation, but there are risks here. Simply adding more sensors and actuators may not give us the comprehensive easy-to-manage water control we seek. We need to fit macro-scale satellite tools, and micro-scale sensors to a meso-scale of system infrastructure.
- **Management of water supply and storage, types, access and volumes.** Water control also extends to water supplies and supply management. Three points apply. First, the volume, location and timing of irrigation withdrawals and depletion will have to match current and future water supplies, both as flows and stocks. This principle emphasises supply management alongside demand management as given by the above principles. If supply and demand are not closely linked, then refilling of stocks and flows in wetter periods will not be sufficient causing greater water shortages during drought periods. Second, irrigators are accessing more types of water (e.g. springs, rain, soil, deep and shallow groundwater, recycled wastewater, on-farm storage). Alongside more efficient irrigation, this greater use of water explains increases in irrigated areas. Some may see 'many waters' as resilience, but if unregulated and unmonitored, then in a connected hydrological cycle, greater consumption of these waters diminishes water availability for others. The third point is that more storage of water is needed everywhere and of every type (e.g. dips and hollows, ghost ponds, soils, streams, on-farm and operational tanks, seasonal storage). In a more dynamic climate, we will need healthy soils and landscapes (green infrastructure) to attenuate, slow down and hold water when it arrives in abundance (Sikka et al., 2018).
- **Managing uncertainty; forecasting and advance water/information communication.** The benefit of enhanced water control should feed through to improved forward notices and planning. Not only will climate forecasting be central to the future of setting irrigation withdrawals and consumption at different risk levels, regularly updated communications regarding water availability and scheduling will also help farmers plan their cropping patterns and irrigation scheduling. In the long run, at-risk legacy irrigation infrastructure not able to secure high assurance water allocations may have to be retired. [I have not worked in or travelled to the Murray-Darling Basin (MDB), and I appreciate there are differing views as to whether their approach to water allocation during drought is successful, but it seems the MDB has much experience on uncertainty and drought-facing irrigation management. (Mallawaarachchi et al., 2020)]
- **Multi-factor, multi-scale water, land, crop performance monitoring / dashboards.** To manage irrigation control and performance upwards, we need information-rich sufficiently accurate models which present easy-to-digest monitoring dashboards (Lankford et al., 2025). On the other hand,

over-simplified models will permit irrigation its ongoing inertia – or to carry on colonising freshwater resources.

- **Technical support and clarity over the change process and outcomes.** Future objectives will need to be expressed, either incrementally per annum or as set objectives, or both. Irrigated systems will need to change either incrementally or rapidly, but will have to move towards specific performance objectives, for example ‘within 5 years this system will operate at a peak supply hydromodule of 0.650 l/sec/ha over x thousand hectares.’ This change towards set objectives requires a tailored participatory service approach to irrigated systems. Every irrigated system, including individual schemes and catchments, is unique. Furthermore, we need to work with **groups** of farmers and linked irrigated systems within a catchment landscape. If we work only with individual farmers or systems, there could be a) less trust, b) inequitable outcomes, and c) loss of peer-to-peer learning.
- **Supported by farming, marketing, technology, water regulation and political systems.** Improving water control cannot happen in isolation – it is tied to wider agricultural and socio-economic and knowledge systems. Many of these systems are changing fast, so information and choice are key here. For example, new cost-effective types of drip tape allow drip irrigation to mesh with canal deliveries improving in-field irrigation efficiency. Other system drivers show inertia which will have to be addressed if catchment water regulation and allocations can fit and support an irrigation sector aiming to perform better and withdraw/consume less water. This may require deep reforms of irrigation water rights and legislation (Libecap, 2011). Political, legal, institutional and technical support for flexible frugal irrigation is required across governments, local councils, funders, research institutes, farmer groups and many other stakeholders – as well as the rules and institutions that govern their decision-making. This principle reiterates that many deep-seated protocols and vested interests exist. (For example, on the technical side, many irrigation engineers do not know about or value the second and third type/pathway given below; they are too dismissive of traditional irrigation (the 1st pathway) and too easily drawn towards the promise of automated pressurised drip irrigation, the 4th pathway).
- **Global and regional-scale co-ordination.** A more systematic catchment approach to irrigated agriculture would be complemented by regional and global assessments and coordination of irrigation, irrigated production and risks to that production. Although lots of uncoordinated irrigation systems seem to be superficially meeting global food needs, food insecurity is shaped by geography, inequality, poverty and gender (HLPE, 2023). In a less predictable future, we will need to know how to affordably feed the world’s population if large areas of irrigated agriculture (especially rice) are knocked out by floods and droughts. UN global food summits are supposed to be the vehicle for this kind of approach but appear to be poorly informed on how irrigation might be governed. This tenth principle would also undertake a global stocktaking of irrigation capacity-building and services.

Action Research and Application of Future Pathways

The next part of the framework takes us to action-research and typologies of irrigated systems for delivering integrated irrigation water control, and the pathways they are currently moving along. This part of the framework aims to work closely with and encourage systems to be better prepared for the future. Although remote satellite sensing and water accounting will be part of change management, the emphasis is on mentoring and partnering (Lankford, 2022).

This action-research sees irrigated typologies and pathways falling into four broad options or characterisations of integrated irrigation water control. The four types are:

1. The first type is termed ‘field watering via water provisioning and distribution’. This first type describes many present-day small and large canal irrigation systems that provide water to fields using extant gate and canal dimensions and visual clues such as water levels to manage water.

Yet on closer inspection this water conveyance and distribution is often without much structure, tight water control or quantitative knowledge of water applications. Systems of this type might see some improvements in the future – but these tend to be via one-off relatively uncoordinated measures such as land laser-levelling and canal lining. Options to better perform might involve switching to types 2 and 3 under irrigation revitalisation or modernisation programmes.

2. Strict structured water supply-led and hydromodule-informed irrigation (Lankford, 1992).
3. Computerised flexible crop-water demand-led – which can be hydromodule informed. This is where individual crop and field water demands are assessed and utilised as the means to determine watering schedules. Such systems usually include row crops, computer control of water, use of sensors, pressurised and piped water distribution, and drip or sprinkler watering. ICID has hosted presentations on this, usually defining it as modern or [modernised irrigation](#).
4. Landscape/ecological/cultural, proxy- or other-led. These are irrigation systems that are culturally and historically embedded within the landscape and are sometimes called traditional irrigation systems (Fernald et al., 2015). Examples include the long-standing acequias of New Mexico. 'Proxy- or other-led', means they currently distribute water using their own unique priorities, indicators and rules. What such systems might miss in terms of a quantitative approach to tight water sharing, they might gain in terms of flexibility, social transparency and acceptability, and priority given to other water uses such domestic provisioning. Such systems commonly experience periods of water abundance and drought and use these lessons to revisit water distribution and to become more climate-attuned, resilient / protective and productive.

To find these types in their pure form is rare; more likely are hybrid types and pathways. For example, a mix of type 1 and 2 would be a very tight field watering design that did not use hydromodules but applied the dimensions of field area (ha), depth applied (mm) and duration (hours) to achieve accurate irrigation scheduling (e.g. 100 mm every 20 days on a fixed area replenishes 5 mm/day ET_o + seepage). A mix of 2 and 3 would be a computerised, piped system where irrigation scheduling is supply-constrained rather than crop water-demand-led. A mix of 3 and 4 might be an old hill irrigation system now adopting drip irrigation. All four forms cover either full or supplementary irrigation, the latter using a combination of rainfall and irrigation.

In the bottom-right hand corner of the framework in Figure 1, is the order, degree, intensity and balance of application of the 10 principles and 8 axes, and the extent that all are applied, individually cherry-picked or are sequenced in a given order. One could envisage that some irrigated systems, for better or for worse, might apply only mild or partial versions of the principles. For example, steps are taken to improve water control but omit deficit irrigation or the capping of consumption to pass those gains to other water users. Systems might also switch from one type or hybrid to another, for example by adding structure and modularity.

Linking the four main parts of the Charter are the two-way red arrows. These signify an iterative mixed participatory approach that envisages many entry points and is both simultaneously bottom-up (because farmers will be implementing many changes) and top-down (in order to remove high-level constraints and help systems to fit their catchments and aquifers) (Haro-Monteagudo et al., 2023).

CONCLUSIONS

The charter is not interested in the superficial form of the irrigated system – and whether it looks modern or traditional. Instead, it is focussed on irrigation functioning to deliver water control. Thus it has kept away from characterisations such as small- or large-scale systems, or commercial versus farmer-led. It does not recommend parachuted-in fashions of different irrigation disciplines (e.g. price water, line canals, metering, soil water sensors) which are usually single-scale hobbyist tinkering, unnecessary and ineffective. The emphasis is on the improvement of integrated water control across large swathes of irrigated land in catchments rather than on a favoured tool or piece of technology. Neither does this

charter see irrigation as climate adaptation or climate mitigation. Water control is a widespread concern regardless of the notional appearance of a single irrigation system.

ACKNOWLEDGEMENTS

Many thanks to Chyna Dixon, Saskia van der Kooij and Louise Busschaert for very their helpful comments and chats prior to this blog being published.

REFERENCES

- Fernald, A., Guldán, S., Boykin, K., Cibils, A., Gonzales, M., Hurd, B., Lopez, S., Ochoa, C., Ortiz, M., Rivera, J., Rodriguez, S., & Steele, C. (2015). Linked hydrologic and social systems that support resilience of traditional irrigation communities. *Hydrology and Earth System Sciences*, 19(1), 293–307. <https://doi.org/10.5194/hess-19-293-2015>
- Haro-Monteagudo, D., Palazón, L., Zoumides, C., & Beguería, S. (2023). Optimal Implementation of Climate Change Adaptation Measures to Ensure Long-term Sustainability on Large Irrigation Systems. *Water resources management*, 37(8), 2909–2924. <https://doi.org/10.1007/s11269-022-03225-x>
- HLPE. (2023). *Reducing inequalities for food security and nutrition* (2023, Issue. <https://openknowledge.fao.org/server/api/core/bitstreams/3b32bc6c-b4e8-46b3-bdae-acc32afe222f/content>
- Lankford, B., Amdar, N., McCartney, M., & Mabhaudhi, T. (2025). The iGains4Gains model guides irrigation water conservation and allocation to enhance nexus gains across water, food, carbon emissions, and nature. *Environmental Research: Food Systems*, 2(1), 015014. <https://doi.org/10.1088/2976-601X/adabe9>
- Lankford, B., & Beale, T. (2007). Equilibrium and non-equilibrium theories of sustainable water resources management: Dynamic river basin and irrigation behaviour in Tanzania. *Global environmental change*, 17(2), 168–180. <https://doi.org/https://doi.org/10.1016/j.gloenvcha.2006.05.003>
- Lankford, B., Closas, A., Dalton, J., López Gunn, E., Hess, T., Knox, J. W., van der Kooij, S., Lautze, J., Molden, D., Orr, S., Pittock, J., Richter, B., Riddell, P. J., Scott, C. A., Venot, J.-p., Vos, J., & Zwarteveen, M. (2020). A scale-based framework to understand the promises, pitfalls and paradoxes of irrigation efficiency to meet major water challenges. *Global environmental change*, 65, 102182. <https://doi.org/https://doi.org/10.1016/j.gloenvcha.2020.102182>
- Lankford, B., Pringle, C., McCosh, J., Shabalala, M., Hess, T., & Knox, J. W. (2023). Irrigation area, efficiency and water storage mediate the drought resilience of irrigated agriculture in a semi-arid catchment. *Science of the Total Environment*, 859, 160263. <https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.160263>
- Lankford, B. A. (1992). The use of measured water flows in furrow irrigation management — a case study in Swaziland. *Irrigation and Drainage Systems*, 6(2), 113–128. <https://doi.org/10.1007/BF01102972>
- Lankford, B. A. (2022). Irrigated agriculture: more than ‘big water’ and ‘accountants will [not] save the world’. *Water International*, 47(7), 1155–1164. <https://doi.org/10.1080/02508060.2022.2088650>
- Lankford, B. A. (2023). Resolving the paradoxes of irrigation efficiency: Irrigated systems accounting analyses depletion-based water conservation for reallocation. *Agricultural Water Management*, 287, 108437. <https://doi.org/https://doi.org/10.1016/j.agwat.2023.108437>
- Lankford, B. A., & Agol, D. (2024). Irrigation is more than irrigating: agricultural green water interventions contribute to blue water depletion and the global water crisis. *Water International*, 1–22. <https://doi.org/10.1080/02508060.2024.2381258>
- Lankford, B. A., & Scott, C. A. (2023). The paracommons of competition for resource savings: Irrigation water conservation redistributes water between irrigation, nature, and society. *Resources, Conservation and Recycling*, 198, 107195. <https://doi.org/https://doi.org/10.1016/j.resconrec.2023.107195>
- Libecap, G. D. (2011). Institutional Path Dependence in Climate Adaptation: Coman's "Some Unsettled Problems of Irrigation". *American Economic Review*, 101(1), 64–80. <https://doi.org/10.1257/aer.101.1.64>
- Mallawaarachchi, T., Auricht, C., Loch, A., Adamson, D., & Quiggin, J. (2020). Water allocation in Australia's Murray–Darling Basin: Managing change under heightened uncertainty. *Economic Analysis and Policy*, 66, 345–369. <https://doi.org/https://doi.org/10.1016/j.eap.2020.01.001>

- Obaideen, K., Yousef, B. A. A., AlMallahi, M. N., Tan, Y. C., Mahmoud, M., Jaber, H., & Ramadan, M. (2022). An overview of smart irrigation systems using IoT. *Energy Nexus*, 7, 100124. <https://doi.org/https://doi.org/10.1016/j.nexus.2022.100124>
- Onyeaka, H., Nwauzoma, U. M., Akinsemolu, A. A., Tamasiga, P., Duan, K., Al-Sharify, Z. T., & Siyanbola, K. F. (2024). The ripple effects of climate change on agricultural sustainability and food security in Africa. *Food and Energy Security*, 13(5), e567. <https://doi.org/https://doi.org/10.1002/fes3.567>
- Rosa, L. (2022). Adapting agriculture to climate change via sustainable irrigation: biophysical potentials and feedbacks. *Environmental Research Letters*, 17(6), 063008. <https://doi.org/10.1088/1748-9326/ac7408>
- Sikka, A. K., Islam, A., & Rao, K. V. (2018). Climate-Smart Land and Water Management for Sustainable Agriculture. *Irrigation and drainage*, 67(1), 72–81. <https://doi.org/https://doi.org/10.1002/ird.2162>
- Talbi, A., Pieter Waalewijn, Poolad Karimi, IJsbrand De Jong, Francois Onimus, Esha Zaveri, Bogachan Benli, Amadou Ba, Ruyi Li, & Skilling, H. (2026). *Nourish and Flourish: Water Solutions to Feed 10 Billion People on a Livable Planet* (Global Water Monitoring Report, Issue. <https://openknowledge.worldbank.org/entities/publication/2807ed57-114f-42f9-b455-12625354383c>
- Ward, F. A. (2022). Enhancing climate resilience of irrigated agriculture: A review. *Journal of Environmental Management*, 302, 114032. <https://doi.org/https://doi.org/10.1016/j.jenvman.2021.114032>