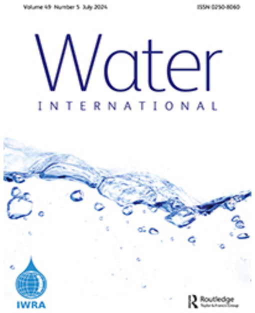

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VIEWPOINT

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Irrigation is more than irrigating: agricultural green water interventions contribute to blue water depletion and the global water crisis

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ABSTRACT
Reflecting on the 2023 assertion by the Global Commission on the Economics of Water that the depletion of blue water by irrigation contributes to the global water crisis, we critique two previous contributions by one of its authors, Johan Rockström. First, to bridge agro-meteorological drought, rainfed (green water) farmers should irrigate. If not regulated, this increases water withdrawals and depletion. Second, the continuum of agricultural water management is a field-scale emphasis on rainfall and/or irrigating to top up soil moisture. This emphasis hinders taking a multi-scale irrigation systems approach to resolve blue water depletion and its inequitable impacts.

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Introduction

The need to properly debate and specify agricultural water management interventions to enhance food and water security is paramount (Ringler et al., 2022). When debating and deciding interventions, we should examine irrigation's material and urgent role in determining significant nexus outcomes between blue water withdrawals, water depletion, food production, greenhouse gas emissions, and the release of water for other sectors (Scott, 2013; Shah, 2023). As we argue in this Viewpoint, irrigation interventions must work with real irrigation systems across scales, from crop and field scales through to basin and global scales. In other words, we should see irrigation and irrigated agriculture as true multi-scale/-dimensional systems (Lankford et al., 2020; Uhlenbrook et al., 2022; Van Oel et al., 2019). However, if we only focus on soil-water deficits at the field-scale to be 'topped up' by either rainfall or by irrigating in a continuum of agricultural water management, we will miss the many system factors that determine cross-scale and globally important nexus outcomes. Simply put, we should be careful of using irrigation occurring at the field scale as a lens to craft policies for irrigated systems.

In the light of this urgency and framing, we find it ironic to see Johan Rockström revisiting his previous poorly specified, inadequately debated and, in our view, incomplete advice on agricultural water management. Via recent publications of the Global

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Commission on the Economics of Water (GCEW, 2023; Mazzucato et al., 2023; Rockström et al., 2023) he argues a global water crisis is underway and its expression and cause is to be found in the over-use of blue water (GCEW, 2023, pp. 10–11), where irrigation is responsible for the majority of this depletion (Mazzucato et al., 2023, p. 26) thereby leaving little to be shared by other sectors. Putting aside the Global Commission on the Economics of Water's problematic framing of a global water crisis (Puy & Lankford, 2024), this Viewpoint accepts the premise that volumes of irrigation withdrawals and depletion are considerable (Döll & Siebert, 2002; Puy et al., 2021), helping to explain the closure of river basins (Molle et al., 2010) and tensions over an inequitable sharing of water (Falkenmark & Molden, 2008).

However, via the Global Commission on the Economics of Water, we believe Rockström is unwittingly commenting on two previous contributions or interventions that were highly influential[1] and continue to have unintended and serious consequences for a blue water crisis in water-scarce catchments and how we respond to it. These were (a) advice to top up rainfed (green water) crops with irrigation (blue water), and (b) to see agricultural water management as a continuum from rainfed crops to fully irrigated crops. The following two sections unpack these interventions, but this quote from the abstract of Rockström et al. (2002) encapsulates both, arguing for the dry-spell top-up and the continuum.

> Finally it is argued that some of the most exciting opportunities for water productivity enhancements in rainfed agriculture are found in the realm of integrating components of irrigation management within the context of rainfed farming, e.g., supplemental or micro irrigation for dry spell mitigation. Combining such practices with management strategies that enhance soil infiltration, improve water holding capacity and plant water uptake potential can have strong impact on agricultural water productivity. This suggests that it is probably time to abandon the largely obsolete distinction between irrigated and rainfed agriculture, and instead focus on integrated rainwater management.

These calls, made over two decades ago, have come to shape rainfed and irrigated smallholder farming policy and training, particularly in dryland areas of sub-Saharan Africa. Accordingly, spurred by the 2023 publications of the Global Commission on the Economics of Water, we feel that it is important to revisit these interventions to highlight their long-term implications for agricultural water management. Our aims are to contextualize this advice and to argue that both interventions see irrigation as the act of irrigating, rather than as complex nested systems bringing varied benefits and costs, and demanding a well-informed debate about irrigation. Given the careers of the authors of this Viewpoint, our focus is on Eastern and Southern Africa, but our overall thesis – the need to distinguish irrigation systems from irrigating – applies to other irrigated river basins and aquifers in the Global South.

To be clear, concerns voiced by Rockström and co-authors (Rockström, 2003b; Rockström & Barron, 2007; Rockström et al., 2010) about the effects of rainfall uncertainty and drought on rainfed productivity, yields and farmer livelihoods, especially in semi-arid sub-Saharan Africa, are valid and important (Biazin et al., 2012; Lebel et al., 2015). However, designing policies to meaningfully address these risks and their impacts on farm production and water resources is notoriously difficult (Gowing, 2018). This is especially so in semi-arid parts of Africa where rainfall is on average <700 mm per year (and is spatially and temporally variable) and annual evapotranspiration rates exceed

1200 mm or more. Often at the forefront of these policies are proposals to withdraw water from surface and groundwater sources to bring irrigation to rainfed farming (Malabo Montpellier Panel, 2018; Morris et al., 2009). However, irrigation leads to high rates of water depletion (as a rule of thumb equivalent to 1.0 litre per second per hectare) via beneficial and non-beneficial evapotranspiration and non-recovery of losses. Therefore, when irrigation expands in command area or over the duration of the annual calendar, increases its dosage, or allows for a change in cropping, it drives up total water withdrawals and depletion. In other words, what starts as a modest call for topping up rainfed soils by irrigating runs the risk of bringing additional water demands to water-scarce catchments (Gowing, 2003).

Increasingly, besides irrigation, there are many calls on limited water in semi-arid catchments from domestic and light industry in growing towns and cities, and for sustaining environmental flows (Lankford & Grasham, 2021; Blanco-Gutiérrez et al., 2013; King & Brown, 2006; Showers, 2002). These sectors and users might rightly argue they exemplify vital societal, human, cultural and ecological uses of water, some of which produce far greater economic and employment benefits than agriculture (J. A. Allan, 1993; Molle & Berkoff, 2009). In the face of this competition, water-withdrawing solutions for rainfed farming should be thoroughly specified, stress-tested and debated lest they add water insecurities to already precarious catchments and aquifers.

Therefore, the two substantive policy questions we raise with this Viewpoint are first, 'should water-withdrawing/-depleting policies to tackle climate/weather vagaries in agriculture, no matter how sensible they seem, be thoroughly specified, debated and monitored before their unintended consequences are allowed to grow?' Second, 'should we move beyond field-scale advice to top up soil-water by irrigating, and instead work comprehensively on irrigated agriculture and systems?' Our answer to both questions is yes; without fully specifying, debating and monitoring irrigation systems, we should judge well-intentioned advice to 'add irrigation' as incomplete and potentially misleading.

Intervention 1: top-up green water by irrigating with blue water

This contribution argued that to bridge agro-meteorological drought in rainfed agriculture in semi-arid savannah areas, farmers should add extra water via supplementary irrigation (Falkenmark & Rockström, 2008; Fox & Rockström, 2003; Rockström & Barron, 2007; Rockström et al., 2010). The paper by Rockström and Barron (2007) suggests a 50-mm dose defines supplementary irrigation. However, this uses a figure supplied by drip irrigation,[2] which is much more controllable than gravity irrigation – see discussion below. Elsewhere, a figure of 60–80 mm of water per season is provided but with no information about the field application method (Rockström, 2003b).

It is important to note that this extra (top-up) watering is possible without significantly depleting water or affecting users downstream as long as five conditions are met.

(1) One is that (subject to water resources assessment and accounting) both command areas and depths of water applied are controlled and/or kept small. However, if area and dosage increase, then the volumes of water withdrawn and depleted by irrigation increase dramatically.[3]

(2) To keep per-irrigation and total dosages small, irrigation application methods must be highly controllable and well monitored. Private farmers and commercial organizations using drip, centre-pivots and travelling rain guns (accompanied by an infrastructure of storage bodies, pipes, metres, pumps, filters, etc.) exemplify such built-in water control. However, this high level of water control requires substantial investments per farm.
(3) Third, that water withdrawal either takes place in humid cooler climates[4] or during the wetter parts of a semi-arid calendar when surplus rainfall and runoff exceeds all-sector needs. It is during these periods that crop water demand can be met by a combination of rainfall and soil water storage. However, it is when wet-season irrigation abstractions (usually set to expect high stream flows) continue into the water-scarce dry season that significant downstream water shortages start to emerge (Lankford, 2004a; McCartney et al., 2007).
(4) Fourth, also subject to water resources management, irrigation can be introduced into semi-arid environments where streamflows are large and dependable enough to accommodate potentially lax regulation. Some of the larger rivers in Eastern Africa (e.g., the downstream reaches of the Rufiji, Tanzania) exemplify such cases. However, achieving command in such locations is not easy, requiring large-scale investments in irrigation headworks which looks unlikely given the current emphasis on farmer-led irrigation in sub-Saharan Africa (Harmon et al., 2023; Izzi & Denison, 2021).
(5) Finally, in theory, rainwater harvested from a small sacrificial uphill donor plot and transferred to a small cultivated plot, optionally via temporary storage in a small pond, can provide more water to the cultivated plot without impacting runoff yield at the catchment scale (Srivastava, 2001). However, hydrological neutrality depends on how donor and recipient plots are designed and scaled up. Furthermore, with regards to this point, even though rainwater harvesting can increase water depletion and cause downstream impacts (Batchelor et al., 2003; Calder et al., 2008), our Viewpoint does not focus on the risks of blue water depletion from rainwater harvesting and the means to manage and mitigate them (Bunclark et al., 2018; De Winnaar et al., 2007). This Viewpoint also does not dwell on the reported widespread failure of rainwater harvesting ponds due to poor site selection, losses and maintenance (Berhane, 2018), even though these risks and failures provide other reasons to question the 'top up by irrigating' advice. Instead, we focus on the consequences of this 'top-up' advice when water is drawn from surface streams, small rivers and shallow aquifers in semi-arid catchments such as those found in sub-Saharan Africa (Morris et al., 2009). We believe the advice, if applied straightforwardly or as a blanket recommendation, runs the risk of significantly increasing blue water abstraction and depletion, described in following eight subsections. The last subsection contains some anecdotal observations of rainfed farmers being unnecessarily encouraged to irrigate.

Ill-considered in-field technologies for applying water

The advice to top up rainfed cropping with water is technically difficult when farmers use surface/gravity/canal irrigation. Furthermore, the supposed alternatives – to irrigate crops with small drip systems and treadle pumps – are by no means technically appropriate or cheap. For example, in Eastern and Southern Africa, for a bucket-and-drip system that might appear to be affordable per sales unit, on a per-hectare basis, the costs are between $10,000 and $40,000/ha,[5] equivalent to other high investment costs for irrigation support (Inocencio et al., 2007; Lankford et al., 2016). A treadle-pump, also a favourite 'top-up' policy solution, is expensive per hectare and on a human labour basis[6] and brings gendered inequities (Palmer-Jones & Jackson, 1997). Blind to their drawbacks and eye-watering per-hectare and maintenance costs, these so-called low -cost technologies were pushed by policy-makers during the approximate period 1995–2010 (Commission for Africa, 2005).

Soil infiltration and absorption and irrigation uniformity across the field

Although on paper the 'top up by watering' advice seems sound, it is technically ill-informed. Adding a single supplementary dose under 50 mm in smallholder gravity irrigation systems is practicably very difficult unless one has drip irrigation, travelling rain-guns or sprinkler irrigators run by high-powered pumps. This inability to carefully dose irrigation occurs because soils, if dry when irrigated by water flowing across a field, will absorb an average of about 70–150 mm of water, double the intended top up. At this point, this larger dose is not 'over-irrigation'. It is a function of the infiltration and absorption rates of tropical and subtropical soils often having total water-holding capacities of between 100 and 300 mm (Landon, 1991).

In addition, unless the field's gradient, size and layout are accurately laid out, and field-edge water control is near-perfect, parts of the field will be over-watered and other parts under-watered. This lack of field irrigation uniformity is very common; it is a function of the difficulty of perfect in-field water control. This is one example of how field irrigation influences patterns of over-watering within a field (see below). Arguably, this lack of uniformity is not the same as over-irrigating across the whole area of the field, but it can predispose farmers to over-irrigating.

Top–tail differences in water supply between canal irrigators

Having set up a canal abstraction system (an appropriate method requiring gravity, labour and cheap materials rather than meeting the capital and recurrent costs of managing pipes and pumps), farmers then face inequitable water distribution. This is seen in the contrast between top- and tail-end irrigators (Chambers, 1988; Wade, 1988). Farmers near the top end of the system have access to more water for more time. They irrigate as if they have access to full irrigation. Tail-end irrigators are usually short of water both in irrigation, volume and timing, and sometimes are effectively rainfed farmers. These differences lend themselves to increases in irrigation near the top end and tensions between farmers that require resolution often via collective arrangements and rules (Meinzen-Dick et al., 2002).

This lack of equity arises because it is rare for smallholders to install enough subsidiary tertiary canals and units with well-designed area, canal and division-gate dimensions and gate types that accurately and evenly distribute a deficit water duty (litres per second per hectare) to all units and within each unit's farms and fields. This weakness in tight system architecture is another example of how poor equity and over-irrigation is structured by design (Lankford, 2023a; Plusquellec, 2002). The problem of taking a purely field-scale view of irrigating is that it misses out how the design of the wider system determines what happens at the field scale.

Extending the area and duration under irrigation

Having established a water demand by opening up rainfed lands with irrigation ditches and canals, we now move to the topic of how this demand starts to grow, again without visible over-watering. With the canal system in place, it is 'easy' for irrigating farmers, especially those at the top end, to switch more of their fields from rainfed crops (e.g., maize) to irrigated crops (vegetables). Or if all their plots are already irrigated, they can grow the area under irrigation, extend into the dry season, or add a second season of irrigation. By these means, a small irrigation system can extend both in area and duration of irrigation. This growth can be aided by adding more abstraction points (surface and subsurface) or by upgrading these informal abstractions with concrete and steel intakes (Lankford, 2004a), all having the effect of encroaching on dry season or drought flows (Lankford, 2004a).

The point made in the previous paragraph about extending into a dry season or drought needs further unpacking, especially in the light of accelerating climate change. Downstream availability of water will be significantly harmed if the advice to 'bridge breaks in the rain by irrigating' is not carefully specified and prescribed. The original advice 20–25 years ago was to limit top-up doses to one or two 50-mm depth-equivalents to maintain soil moisture levels until the next rain arrived. However, as farms enter the dry season or drought, the amount of water needed to sustain crop growth matches more of the total crop water requirement, which can be 500–600 mm or more. The problem is that policy distinctions between 'a single supplementary irrigation during a temporary dry spell', 'mixed rainfed/irrigated crop production during a normal season' and 'full irrigation during a dry season or drought' may not be flexibly and clearly expressed, or robustly enforced. As climate change increasingly expresses itself through increased rainfall variability, floods and droughts (Thornton et al., 2014) and higher rates of evapotranspiration (Marshall et al., 2012), the original advice applied to deal with breaks in normal/wet season rainfall runs the risk of segueing into full irrigation (Burney et al., 2010; Domènech, 2015), thereby adding to blue water depletion.

Structured and accidental over-watering increases depletion

Farmers can easily over-water their fields. This excess watering adds to water depletion unless we can be certain that 100% of excess watering runs back to the catchment or aquifer for other users (see next section). Over-watering can happen in two ways; first, by having irrigation systems that make it easy to over-irrigate; and second, by deliberate or accidental over-watering. Although these are difficult to distinguish in the field and both can be addressed by targeted management, they are explained separately.

Structured over-watering

Inferior irrigation designs can make it easy for farmers to irrigate inaccurately; in other words, their design makes it easy to over-irrigate. This occurs when the physical design of the field, farm or canal system unwittingly encourages farmers to add too much water. For example, a flooded rice system using small bunded plots (sometimes called paddies) without canals will see deeper standing water in the top-end plots than those further downslope. This is because water cannot easily overcome the hydraulic resistance of the many soil bunds/ridges to drain downhill. The simple act of adding in canals would distribute some of the top-end excess lower down the system.

Yet, the presence of canals and division gates can still structure over- and under-watering. Where canals provide water to tertiary units, a poorly designed ratio of supply-to-area will over-supply some tertiary units (where this ratio is, say, above 1.20 l/s/ha) and under-supply other units where the ratio is <0.80 l/s/ha (Lankford, 1992, 2023a). Structured over-watering can also be social in nature; for example, where water user associations are absent or weak, resulting in poor canal management and scheduling.

Deliberate or accidental over-watering

This occurs when farmers have put in place physical and institutional structures to distribute water accurately but choose to over-water their fields, depriving neighbours of water. This choice may be deliberate if they believe they are 'banking' water in fear of not receiving the next scheduled rotation in time, or accidental if they (a) genuinely believe the soil and crop needs more water, or (b) are absent from their fields when they should be present to control water. Although accidental and deliberate over-watering can be addressed by structural improvements and tighter social agreements, it can also be monitored and discussed using soil probes (García et al., 2021).

Return flows from leaky irrigation do not save the day

Agreeing with Lankford et al. (2020), we disagree with the consensus that all losses from irrigation (the balance not consumed in evapotranspiration) are beneficially recycled and reused downstream, as suggested by Perry et al. (2023). On the contrary, most losses meet other fates. Some are reused within the command area of the irrigation system, giving higher classical efficiency but which can bring costs such as delayed scheduling (Lankford, 2006) or increased salinity (Keller & Keller, 1995). Or rainfall runoff can mix with and be mistaken as irrigation drainage losses. Or depending on land area, slopes and geology, irrigation losses become unrecoverable. As an example of the latter, take the Rift Valley in Eastern Africa in the cases below. This is a mountainous area covering thousands of square kilometres containing gigatonnes of unweathered or weathered rock able to absorb irrigation losses, rainfall and streamflows without reissuing them as easily recoverable flows for second use by irrigators. The complicated fissured geology and mountainous physiography of Eastern Africa is not equivalent to the flat floodplain sediments of the Nile delta or the Lower Indus which are able to promptly absorb irrigation losses for reuse by farmers using shallow tubewells (Molle et al., 2018).

A new impetus from 'building resilience to climate change'

Addressing the policy that believes adding irrigation helps build resilience to climate change (Nangia & Oweis, 2016), this Viewpoint is worried that legitimate concerns with climate change are creating a technical and institutional environment conducive to, or to justify, blue water withdrawals even when they are not necessary. For example, in Kenya, rainfed farmers are encouraged to harvest and store water to irrigate due to climate uncertainties without regard to their cumulative effects on the catchment or whether rainwater harvesting micro-dams work. Furthermore, this adds to water insecurities as wealthier upstream farmers with larger or deeper pumps compete against poorer, smaller, shallower, downstream irrigators.

Anecdotal evidence of rainfed farmers encouraged to irrigate

Both authors have witnessed rainfed farmers being encouraged to irrigate where, we believe, it was not an urgent agronomic input. In 2003, the first author witnessed the promotion of small-scale irrigation near the town of Mbeya in Southern Tanzania by Ministry of Agriculture extension officers encouraging rainfed farmers to irrigate. It seemed that no stream or spring was small enough to be protected from irrigation. Yet at this altitude of 1700 m, irrigation was not necessary; soils were rich and deep as a result of Rift Valley volcanic rock weathering, and rainfall was approximately 800–1000 mm during the rainy season, sufficient to meet maize's water requirements, albeit with some unpredictable variability. This irrigation subtracted water that should have remained in the streams heading down towards settlements and villages and then on to the increasingly water-stressed Usangu wetlands and subcatchment (McCartney et al., 2007).

The second author toured small rainfed farms in different counties in Western Kenya (e.g., Kakamega, Vihiga, Kisumu, Siaya, Busia) in 2021 exploring conservation agricultural practices. Here, farmers cultivated horticultural crops such as maize, kale, spinach, squash and so on. They were advised by staff from non-governmental organizations, parastatals and government departments (e.g., Kenya Agricultural and Livestock Research Organization or KARLO) to harvest water and dig shallow wells to store water for supplementary irrigation during dry spells. Small-scale farmers were also encouraged to invest in water pans, boreholes, and water pumps to help with supplementary irrigation. (This encouragement has been going on for at least 10 years, as witnessed by Agol). In some of the farms, crops were stunted growth with yellowish leaves most likely as a result of over-watering. One farm owner said 'I think I put too much water on my maize crop without realizing it, as you know rainfall is rather unpredictable.' The risk with supplementary irrigation is that rainfed farmers can be encouraged to irrigate their soils when it is not needed.

Subject to highly specific prevailing agro-meteorological and agronomic conditions, managing soil moisture via supplementary irrigation may not necessarily optimize or maximize yields. In the authors' experience it is sometimes difficult to know whether too little or too much water is present in the soil because both can show up as crop leaf stress and stunted growth. Blanket advice to rainfed farmers to irrigate a priori assumes they are without water or are likely to need water. Too much/little moisture in the soil profile might not be obvious to a farmer often lacking an interest or methods to ascertain soil moisture from (a) field-scale tools to monitor soil and crop moisture conditions (Ahmed et al., 2023); (b) access to satellite-based monitoring (Piedelobo et al., 2018); (c) system-scale infrastructural means to schedule irrigation between groups of farmers (Lankford, 1992, 2023a); and (d) finger-feeling moisture using soil augers and spades (Klocke & Fischbach, 1984). A different way to engage with farmers would work with these four methods to support cross-scale decision-making so that they can collectively weigh the costs and benefits of agronomic inputs, and the means to determine them.

Intervention 2: the continuum of agricultural water management

The second contribution argued there is a continuum in agricultural water management from rainfed farming to rainwater harvesting to supplementary irrigation to full irrigation (Rockström et al., 2010). This intervention says the distinctions between them should be removed. There is no doubt that observations of different kinds of crop-watering systems in different localities provide evidence of a continuum of watering types, and that in some locations a rainfed system can evolve to be partially and then fully irrigated. However, such *ex post facto* perspectives do not easily instruct scientists and policy-makers how to administer and design hybrids of these different watering types.

Appealing as this inclusive advice is, it harbours risks for how we differentiate and specify policies for managing extant irrigated systems, their water productivity and effects on blue water withdrawals, depletion and sharing. The instruction 'abandon the largely obsolete distinction between irrigated and rainfed agriculture' is, we believe, an undifferentiated field-scale view of where and how crops get their water. We explain this in the following two subsections.

Small or category-type differences between watering systems?

The risk of placing crop watering types on a continuum is that we fail to properly distinguish the salient properties of one type from another. Figure 1 argues that in moving to the right along the spectrum of types (see x axis of the graph) we do not simply encounter bigger, wetter or bluer versions as a linear evolving phenomenon. Instead, the continuum should be viewed as one of geometric growth of complexity. Thus, although rainfall, rainwater harvesting and very controlled supplementary irrigation can bring 50 mm of water to an area of 0.5 m^2 to 10,000 m^2, delivering many irrigation doses of less than 150 mm for crops within gravity systems 10, 100, 1000 or 10,000 times bigger is markedly more complex. This is because the system grows spatially but also adds nested/hierarchical levels to the irrigation scheme; field; farm, tertiary unit, secondary, main, etc. With each additional lower level, containing more flow bifurcations, comes even greater social and technical difficulties in accurately controlling farm flows, ratios, and field irrigation doses.

To further make the case for distinguishing between types of soil–crop–water management we quote directly from two previously voiced concerns, the first contained in Box 1 is about the differences between rainfed and irrigated farmers (Lankford & Orr, 2022) and the second (Box 2) discusses the difficulties of managing large-scale irrigation

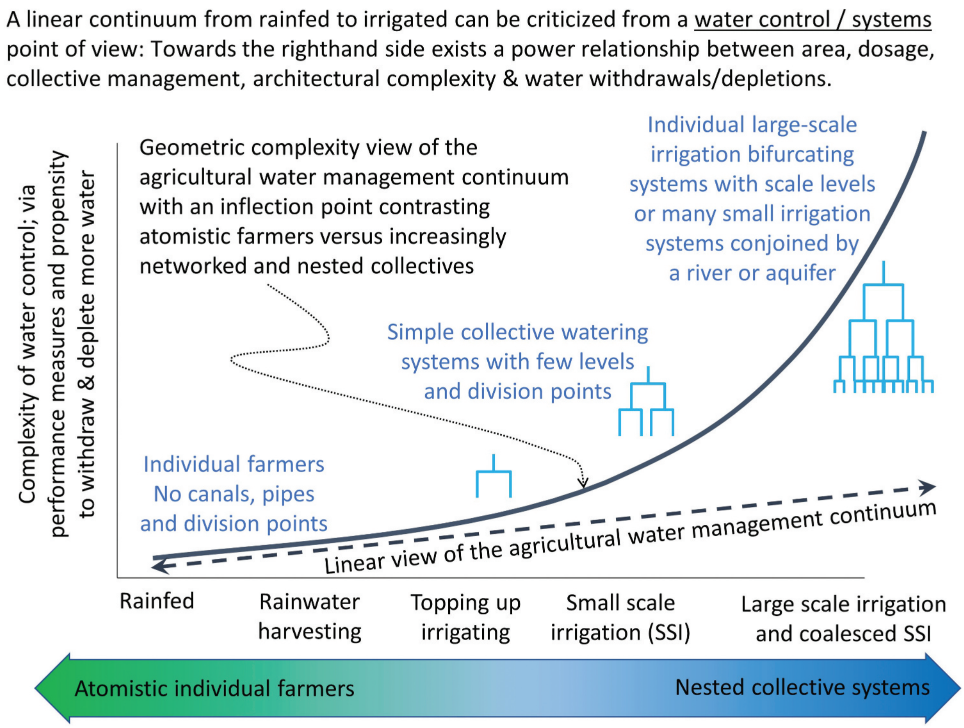

Figure 1. A geometric versus linear view of the agricultural water management continuum.

Box 1. From page 11 (Lankford & Orr, 2022) in a section titled 'Irrigated RA is Categorically Different to Rainfed RA' (where RA is regenerative agriculture).

Under rainfed agriculture, soil moisture is managed indirectly by acting on soil and land properties and processes (via cropping, ploughing, soil ridges and so on). With irrigation, soil moisture levels are directly managed via adjusting the irrigation scheduling parameters (depth per dose, frequency, placement, duration etc.). While there are real challenges for both rainfed and irrigated agriculture, to adjust the irrigation parameters so that wasteful or over-depletive irrigation (or indeed under-irrigation) does not occur requires an array of scale-related technical, social, political and economic problems to be solved (Lankford et al., 2020). This is because in irrigation, water is withdrawn, conveyed, distributed, applied, consumed, drained away, slowed down and contaminated with salts or agrochemicals. At each stage there are errors, opportunity costs for, and perspectives on, that water.

Box 2. From page 8 (Lankford et al., 2016), emphasizing the size of large-scale systems.

We make the point that 'large' is not simply a bigger version of 'small'. To explain this we critique Rockström et al. (2010, page 548) who proposed 'A natural consequence of a re-orientation of water resource management, starting from rainfall as the freshwater resource, is to abandon the current (artificial) divide between irrigated and rainfed agriculture'. While we acknowledge that crop watering technologies span from purely rainfed to fully irrigated, we consider that 'a continuum' is not the most appropriate starting point from which to view large-scale systems.

A different starting point is to consider that the difficulty of water control increases geometrically as systems go from 1 hectare to 10 to 100 to 1000 to 10,000 hectares (and on through to >1 million hectares). This non-linear effect of system size on water control asserts that an inflexion or tipping point exists and that remarkably different types of systems exist on either side of this point. At the small-scale, farmers are more likely to be socially connected, more likely to own the whole of their irrigation system, more able to meet to discuss water, and more likely to be able to distribute water equitably. But in large hierarchical systems these phenomena are very different; accurate water control is difficult, infrastructure ownership overlaps and irrigators cannot socially connect except to close neighbours. The continuum perspective cannot adequately inform large-scale irrigation policy (or indeed policy about large coalesced areas of small-scale systems). On the contrary, it is the recognition of differences in system size, structure and ownership that is the premise for a new approach to large-scale irrigation systems.

systems (Lankford et al., 2016). Summarizing these two text boxes and Figure 1, the systemic technical and social challenges of water management grow exponentially when we move from rainfed to irrigated agriculture and from small to large irrigation systems or from a catchment containing a few small-scale systems to a catchment containing a large coalesced area of many small-scale systems (Lankford & Hepworth, 2010). As we move to the right-hand side of Figure 1, irrigation moves from being a top-up of soil water delivered artificially towards becoming a true system comprised of myriad material and human dimensions, and technical and social perspectives.

Not defining what supplementary irrigation means

Within the continuum, 'supplementary irrigation' should be carefully defined. Supplementary irrigation should not only be seen as a system of rainfed farming topped up by irrigation, or an intermediate stage between rainwater harvesting and irrigation. It should also be seen as an established system of irrigated farming where rainfall is insufficient to grow the desired crop (Perrier & Salkini, 1987). When rainfall does occur, rain is supplementary to the water provided by irrigation – thereby distinguishing it from full irrigation (Perrier & Salkini, 1987). This rainfall contribution is either designed into the irrigation system in the calculation of its water duty (Allen et al., 1998), or it is culturally and informally understood by farmers with a long tradition of working with water scarcity. In an example of the latter, witness the deficit *warabundi*[7] sharing of scarce canal water flows in parts of South Asia (Abernethy, 1990; Anwar et al., 2016). Here, farmers flexibly change their irrigation area and scheduling depending on varying rainfall and canal flows. In nearly all the cases of supplementary irrigation (e.g., in Cyprus, Turkey, Morocco) described by Perrier and Salkini (1987), authors describe irrigation systems operating in semi-arid conditions rather than purely rainfed systems benefitting from a dose or two of irrigation.

These seemingly subtle differences matter; experienced irrigators adapt, self-regulate and reschedule their water applications. Rainfed farmers with no history of irrigation must learn how to do this. If ill-defined, 'supplementary irrigation' encourages extension officers to tell rainfed farmers to abstract water when it is not necessary.

Capacity building for agricultural water management

One serious consequence of 'the continuum' arises when considering a capacity-building curriculum to teach agricultural water management to a new generation of scientists. The first author of this Viewpoint helped compile a report funded by the International Water Management Institute to specify a future academy and capacity-building programme on agricultural water management. Lankford subsequently co-chaired a stakeholder meeting organized by the Water Research Commission and the International Water Management Institute in South Africa in April 2023 to present and discuss the report. The report is being published as a journal article (Lankford & Mabhaudhi, 2024).

Within this study and at the 2023 meeting, Lankford and Mabhaudhi argued for a special emphasis on irrigated agriculture by relaunching new irrigation Masters programmes.[8] Regarding this emphasis on irrigation, not all participants of the meeting agreed, pointing out that all types of agricultural water management should be taught.

However, if all of the agricultural water management topics are contained in a one-year MSc course (with 20 weeks in the classroom) less time will be dedicated to teaching irrigation, which means the many complications of irrigation will be contained in only one or two modules. As such, we will continue to produce graduates who, in the coming decades, will not be able to help diagnose and help solve blue water scarcities and inequities simultaneously sustaining and boosting crop production. The situation is serious; the authors of this Viewpoint encounter many water graduates and early-to-mid career experts who have little in-depth irrigation knowledge, or willingness or capability to see irrigation as complex.

Discussion; thoroughly specified and debated irrigation interventions

The 'top-up soil water' advice and the 'agricultural water management continuum' present a useful introductory framework for discussing types of soil–crop water management facing the risk of dry spells and droughts. The two interventions introduce agricultural water for the benefit of non-specialist decision-makers, and form a teaching introduction to soil water management (as Lankford has done during his university teaching). At the field scale, both interventions correctly say crop roots do not know where their water comes from: a shallow water table, rainfall, rainwater harvesting, or irrigation.

However, if we agree there is a blue water crisis (GCEW, 2023) starkly expressed in river basins comprising significant areas of irrigation, the agricultural water management types present differently. Encountering reality, especially in water-scarce catchments, the agricultural water management continuum becomes less instructive. Let us look again at Rockström et al.'s (2002) advice and reflect on how it helps to solve or hinder today's blue water problems: 'it is probably time to abandon the largely obsolete distinction between irrigated and rainfed agriculture, and instead focus on integrated rainwater management'. Yet, we note, their 2002 paper did not accompany this advice with irrigation systems knowledge or a regulatory framework to govern growing water withdrawals and depletion originating from many diffuse rainfed farmers wishing to add irrigation. We believe this omission fails to halt irrigation's growing water withdrawals and consumption from atomistic rainfed individuals as well as from small- and large-scale systems. In short, we cannot have our cake and eat it; we cannot have irrigation at the centre of a growing blue water crisis and yet (a) encourage rainfed farmers to irrigate and (b) neglect to see the category differences between rainfed and irrigated farming.

The impact of this early 2000s thinking continues to this day. As argued above, we think irrigation is being swallowed by an all-encompassing agricultural water curriculum and discourse. The subject of irrigation requires a more knowledgeable approach, which unfortunately is diminishing. We have too many water managers and scientists who do not understand irrigation very well, including its social and technical specification.[9] During the authors' work in the field, we saw state and non-state technical advisers and extension officers often advising farmers to irrigate without an in-depth understanding of its techniques and consequences. Furthermore, studies about staying within a blue water planetary boundary fail to sufficiently link blue water consumption to agricultural green water policies instead focusing on other drivers (Stewart-Koster et al., 2024).

It is not only unwarranted water withdrawals that reveal how the continuum stops us from seeing the risks and complexities of irrigation. This Viewpoint believes that when irrigated agriculture is thought of as just another version of watering soils (instead of irrigation as a complex system) we draw-up field-scale interventions rather than system-diagnosing tools. This means we focus on irrigating means (e.g., solar-driven water pumps) or tools to improve field watering rather than crafting system tools to examine whole systems (Renault et al., 2007). In our personal view, the Chameleon wetting front detector[10] is one example of a tool, attracting claims for its efficacy in improving water productivity (Schmitter et al., 2017). We accept wetting front detectors can act as an intermediate object to solicit farmer discussions (Stirzaker et al., 2017). However, being a point-source detector, the Chameleon cannot easily operate technically at scale, deal with soil and field variabilities, or unpack systemic dimensions of irrigation (Lankford, 2023a).

Given the consequences of demand-driven growth of all types of the agricultural water continuum – but especially irrigation – on blue water nexus outcomes, they should be distinguished from each other and thoroughly specified and debated. We now explain why we have used the term 'specified and debated' in this Viewpoint. It relates to how we comprehend irrigation. We either under-estimate irrigation and interpret it to mean watering, or we more fully appreciate its systemic complications, consequences, and puzzles. The balance between these perspectives can be seen in the way scientists specify and debate irrigation.

Specifying irrigation and understanding irrigation systems

'Specifying' starts with understanding how irrigation systems behave as dynamic scale-based entities that in turn shape the way water and people in those systems behave. One irrigation system, say, of 100 ha might comprise a tightly designed, rigidly controlled rotational schedule providing water on a 12-hour basis to 1-ha plots each directly connected to a main canal and drain network. Another irrigation system of 10,000 ha might comprise a looser arrangement with 24-hour supply, few hierarchical secondary and tertiary canals, and no drainage system. In the latter, irrigation water is passed around in a less-controlled manner and farmers have to contend with the downsides of night-time irrigation (Chambers, 1988). With this understanding, specifying irrigation means detailing, diagnosing, adjusting and working with its components; how size, canal and pipe architecture, landscape, hydrology, agrometeorology, soils, crops, energy, farmers, operators, etc. combine in unique systems of water control that do or do not match their context and intentions (Denison et al., 2022; Renault et al., 2007).

If we see irrigation only as the act of irrigating, we will fail to specify and analyse these system characteristics, and therefore under-estimate the systems nature of irrigation. When asking rainfed farmers to irrigate, we will omit to add the regulatory and knowledge services to govern water management over different spatial and time scales. Looking at the agricultural water continuum literature (Fox & Rockström, 2003; Rockström, 2003a; Rockström et al., 2002), we see its 'add water' instruction and some hedged concerns about downstream impacts of rainwater harvesting, but we cannot find any advice on the proficient technical and institutional management of irrigation systems and the broader water governance of irrigated catchments.

Debating irrigation

There is less to debate if our definition of irrigation is simply the act of conveying water to a soil. Relatively mundane discussions regarding doses, infiltration rates, canal dimensions, pipe materials, field levelling, or wetting front detectors come to mind. Any debates about these subjects are constrained by their placement within a scale, for example, the field level. However, stakes climb if we see irrigation represented by multi- and cross-scale systems positioned to face water scarcity and climate change in the next 10–40 years, comprising many material and human dimensions and consequences. The following exemplify significant debates and questions:

- How to formulate catchment and aquifer water governance to an S-shaped curve of accelerating irrigation growth is no easy task (Lankford, 2003). There are many aspects to this, including the need for water monitoring and accounting (Perry et al., 2023), revising out-of-date water legislation (Schreiner & van Koppen, 2020), and tracking how gains in irrigation efficiency during drought lever irrigation growth in the periods between droughts (Lankford et al., 2023).
- We should be debating long-held protocols for irrigation planning. It seems to us that Rockström's interventions 20–25 years ago represent an abundance paradigm of water resources in semi-arid catchments. However, these days, there is little spare water available for irrigation when seasonality, climate change and other growing water demands are accounted for. A sense of widespread spare water has echoes with how well-established FAO crop water requirement procedures continue to dominate irrigation planning (Allen et al., 1998). These procedures have to be replaced with a scarcity paradigm that recognizes the many pressing calls on a catchment's water (Lankford, 2004b).
- We should debate how best to share out limited water in semi-arid catchments, especially to sustain and boost rainfed agricultural production. One solution is to use blue water to supply growing villages and towns whose services and demand for food in turn stimulate rainfed farmers to adopt non-irrigation practices that raise yields. In this way, blue water supplied to towns acts as a vector to green-water farmers (Lankford & Grasham, 2021).[11]
- There is an unresolved debate about how to modernize and improve water control on gravity irrigation systems (Bolding et al., 1995; Plusquellec, 2002) in ways that do not go down the drip irrigation route. This requires us to agree that (a) swathes of existing irrigation infrastructure could benefit from a tighter architecture of water control; and (b) that drip irrigation is not suitable for field crops or for smallholders less able to source cheap energy, and cover drip's maintenance, operation and depreciation costs.
- When rebuilding capacity in agricultural water management, we need to debate its curriculum. Should teaching be across the whole agricultural water continuum or focus on irrigation? The problem with teaching across the continuum is that it gives little room for the many technical, social and legal dimensions of irrigation, each of which are very detailed subject areas. If we prioritize irrigation, how might we teach it not as 'the act of watering' or something to be planned using FAO protocols (fine if land and water is abundant; Lankford, 2004b) but instead as an *n*th-dimensional

puzzle in a resource-limited world. If the latter, irrigation requires formal and customary management and regulation drawing on many tools, actors, disciplines, knowledges, and services. This requires a subtle change in irrigation pedagogy in turn related to our (expert) perspectives on the knowledge, roles and agency of irrigators. For example, tools for managing large areas of irrigation are not necessarily soil moisture probes brought by external experts aiming to replicate normative, field-station or commercial orchard–crop irrigation agronomy.[12] Among other methods, we favour serious games to get farmers to discuss how they distribute water and then ask for additional services (Lankford et al., 2004).[13] Soil probes are not redundant here, but they should be placed within a brokerage and service model willing to solve under- and over-watering by tightening up system design architecture and fostering collective knowledge.

- Following on from the previous point is the question, what is the scarce resource in semi-arid irrigated catchments? It is rational to answer 'water' when irrigating is our refracting lens. But taking a systems view, which includes farmers (Duker, 2023), the scarce resource is the acuity and democratic vitality of farmer-group knowledge and learning, with water as the communication medium. Because unless farmers, supported by knowledge services, resolutely assess their systems in cross-scalar and many-factor ways, they are more likely to be co-opted into the latest water solutions.

Conclusion

Summarizing our two concerns, first, supplementary 'irrigating' should not be seen as the automatic, natural and universal solution for the vagaries and vulnerabilities of rainfed farming, unpalatable as that policy advice may be. Irrigation is not needed in all circumstances, and we are no longer in a water-abundant world that can afford ungoverned increases in irrigation withdrawals and consumption (Lankford, 2004b). When irrigation is accessed and developed initially as minor 'top-up' volumes, it runs the risk of rapidly expanding, thereby depleting more water within water-scarce catchments (T. Allan, 2019; Oduor et al., 2023). Second, given the considerable blue water problems faced by many irrigated river basins, it is time to reflect on today's utility of the continuum of agricultural water management in order to see the category-type differences between rainfed and irrigated systems. However, this caution is not seeking to swing the pendulum to a situation where water resources, keeping in mind environmental and other sector needs, are not developed for agricultural production and protection.

As a coda to this Viewpoint, we believe the lack of irrigation understanding, specification and debate seen in the original Rockström et al. literature continues in the 2023 main and technical reports of the Global Commission on the Economics of Water. We will not be able to govern irrigation – and by extension the global water crisis – if we see irrigation only as watering crops, a technology choice (e.g., drip versus canal), as part of the continuum of agricultural water, or as a sector that would benefit from increased efficiency. (The fault with the latter is that only one factor controlling water depletion, efficiency, is invoked – see Lankford, 2023b). The seemingly natural, expert solutions found in the 2023 Global Commission's reports, such as capping withdrawals and depletion, pricing water, and adding precision irrigation, are a mish-mash of ideas, revealing how much is missing from a coherent comprehension of irrigation and irrigated catchments as complex cross-scale multi-dimensional systems.

Notes

1. According to Google Scholar the number of citations for the four Rockstrom et al. publications about the two interventions exceed 850, but many of these will overlap within subsequent papers.
2. Citing Sivannapan (1992).
3. A simple calculation demonstrates this; 50 mm applied over 500 ha is 250,000 m^3 of water whereas 100 mm applied over 1000 ha is 1 million m^3 or four times the volume of water. As well as these modest figures showing that [depth × command area] drives increased water withdrawals/depletion, it should be remembered that it is easy for farmers to increase their application depths and areas (contributing to blue water depletion) and yet still be under-irrigating.
4. Cereal and potato farmers in the temperate/oceanic climate of East Anglia, UK, successfully use high-pressure travelling rainguns to apply doses of approximately 15–30 mm to bridge gaps in rainfall. This is a good example of a supplementary irrigation method where the advice to top-up soil water is valid and technically feasible.
5. Approximately \$20–\$65 per kit per 10–20 m^2 area covered (Sijali, 2001). *Drip Irrigation. Options for smallholder farmers in eastern and southern Africa* (Regional Land Management Unit, RELMA/Sida, Issue. See also https://www.aquahubkenya.co.ke/cost-of-drip-irrigation-per-acre/.
6. It escaped the notice of those favouring treadle-pumps that for millennia humans used animals to lift water.
7. 'Warabandi is a system of rotation of supply of water according to a predetermined schedule as per area and crop needs, specifying the day, time and duration of supply to each holding to ensure equitable water distribution among farmers of an outlet command'. https://goawrd.gov.in/faq/what-warabandi.
8. When the first author took his MSc in Irrigation in 1992, students could pick from about six or seven Irrigation MSc/MEng degrees globally. Now there are none.
9. These observations are corroborated by senior staff at the International Water Management Institute and Water Witness International who have remarked on the difficulty of recruiting new staff with extensive irrigation knowledge.
10. 'The Chameleon sensor gives a measurement of soil suction across a range similar to a tensiometer. A suction (or tension) reading relates to the stress experienced by a plant, so unlike a water content reading, the interpretation is independent of soil type. The physical measurement is the electrical resistance of a porous sensing material packed between two electrodes'. Stirzaker and Driver (2024). Soil water sensors that display colours as thresholds for action. *International Journal of Water Resources Development*, pp. 1–19. https://doi.org/10.1080/07900627.2024.2322153.
11. It was after presenting the vector-water idea to a May 2010 workshop in London that Tony Allan emailed Lankford the next day paraphrasing the idea and its underlying concerns as 'hesitate to irrigate'. In his email he wrote 'And especially for the best idea of the day – hesitate to irrigate and ensure municipal and industrial water for the towns so that reliable purchasing power for the rainfed production of the green water can be put in place' and 'Avoiding future impossible demand management politics and the loss of the environmental services of water are the additional major benefits. The leadership of FAO needs to know'.
12. With a first degree in Soil Science, Lankford has much experience using tensiometers and a neutron probe in the 1980s. However, more time-effective and accurate means to schedule irrigation over large areas sit with other technologies – see Lankford (1992).
13. After running the River Basin Game in Southern Tanzania in 2003, irrigators asked for training on book-keeping, not on soil and water management. To help run their informal

water user association, they argued their knowledge gaps were social and financial, rather than technical.

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