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A scale-based framework to understand the promises, pitfalls and paradoxes of irrigation efficiency to meet major water challenges

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ABSTRACT

An effective placement of irrigation efficiency in water management will contribute towards meeting the pre-eminent global water challenges of our time such as addressing water scarcity, boosting crop water productivity and reconciling competing water needs between sectors. However, although irrigation efficiency may appear to be a simple measure of performance and imply dramatic positive benefits, it is not straightforward to understand, measure or apply. For example, hydrological understanding that irrigation losses recycle back to surface and groundwater in river basins attempts to account for scale, but this generalisation cannot be readily translated from one location to another or be considered neutral for farmers sharing local irrigation networks. Because irrigation efficiency (IE) motives, measures, effects and technologies play out at different scales for different people, organisations and purposes, and losses differ from place to place and over time, IE is a contested term, highly changeable and subjective. This makes generalisations for science, management and policy difficult. Accordingly, we propose new definitions for IE and irrigation hydrology and introduce a framework, termed an 'irrigation efficiency matrix', comprising five spatial scales and ten dimensions to understand and critique the promises, pitfalls and paradoxes of IE and to unlock its utility for addressing contemporary water challenges.

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1. Introduction

A growing global population, rising demand for food and declining water availability due to increasing use from all sectors are driving an international debate on how water is measured, valued, used and managed (Gosling and Arnell, 2016; Konar et al., 2016; Steduto et al., 2017). Irrigation is the largest consumer of freshwater resources globally; it is at the centre of debates regarding water allocation as demands for water change (Elliott et al., 2014; Haddeland et al., 2014) and is often cited as being a profligate and inefficient use of water (FAO, 2017). These interests emphasise recent often-contested issues of 'irrigation efficiency' and 'saving water', even though promoting improvements in water management within agriculture has long been an international policy objective (Rosegrant et al., 2014). Irrigation efficiency thus intersects with a wide range of sustainability concerns as illustrated by reference to efficiency in the Sustainable Development Goal 6 (UN, 2017) as SDG Target 6.4; "By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity."

Despite its apparent simplicity as a ratio, irrigation efficiency (IE), as an empirical calculation, management practice, sustainability measure and policy goal is far from straightforward. Accordingly, as we explain, there is a grave risk of it poorly serving the resolution of these water and food challenges and/or leading to unintended or paradoxical consequences. Examples of this include Grafton et al. (2018) who argued for greater policy awareness that raising IE could paradoxically increase water consumption from irrigated farming systems. This phenomenon occurs because, it is asserted, irrigation losses that were previously recovered elsewhere in the catchment, switch to consumption in the form of crop transpiration (Ward and Pulido-Velázquez, 2008). However, if overly generalised, this paradox is also unreliable because the fates of losses, before and after changes to irrigation technology and efficiency, are not predictable. For example, waterlogging, small wetlands within or peripheral to irrigation systems, salinization, and evaporation from patchy or young crop growth indicate that irrigation water losses are not always recovered usefully and rapidly to aquifers and streams. Therefore, reducing these types of non-returned losses will help cut net water depletion. Other authors (Dumont et al., 2013; Hammani et al., 2017; Lankford, 2013; Scott et al., 2014) have identified conceptual and operational questions over the paradoxical hydrological and institutional fates of IE water 'savings' arising from the pursuit and implementation of IE, including the need for limits in irrigation expansion or new non-farm uses of 'saved water'.

Furthermore, with reference to the water action track on 'water productivity' in the 2019 Global Commission on Adaptation report (GCA, 2019), IE is variously linked to crop water productivity (WP) depending on circumstances. For example; a) higher IE can, as a result of lower 'losses' in the WP denominator, reflect greater transpiration correlated with higher crop growth and higher WP, or; b) higher IE resulting from changes to infrastructure and equipment can raise costs and reduce the net crop value in the WP numerator in turn reducing WP, or; c) a lower IE impacts crop stress and reduces productivity by slowing the timing of water delivery between neighbouring irrigators sharing a local network (Lankford, 2012a), or d) a higher IE can reflect the maintenance of a more uniform soil moisture within a field leading to higher WP (Playán and Mateos, 2006).

With scope for misunderstanding and misapplication, IE is often used loosely by different actors, an observation discussed by several scholars (Kuper et al., 2017; Van Halsema and Vincent, 2012). While we should not berate a desire to do better with less (and a vernacular language associated with such concerns), we are fundamentally concerned that influential groups such as investors, consultants, companies, researchers and scientists, policy-makers, NGOs and environmental practitioners, as well as farmers, agricultural and water resource managers, are developing poorly or partially informed IE beliefs. These actors can hold persuasive 'reinforcing' views on IE and associated efficient technologies (Venot, 2017) despite a clear lack of appreciation of; a) relevant debates on, and evolution of, the subject (Lankford, 2012b; Van Halsema and Vincent, 2012); b) the multiple hydrological scales, viewpoints, and gains and losses associated with changing irrigation efficiencies (Molden et al., 2010); and; c) the significance of differing socio-technological and agroecological contexts, marketing incentives, and political economy pressures which apply to irrigated agriculture (Kuper et al., 2017).

Furthermore, contrary to a view that assumes that there is a single 'dimensionless' definition of IE (often held among irrigation engineers), we argue there is a need to recognise not only multiple perspectives on IE, but also the coexistence of multiple definitions and calculations of IE (see below and Appendices A, B and C). In other words, multiple or hybrid definitions and proxy measures of IE can be tailored to tackle current complex water management challenges which are currently not well served through difficult-to-measure, conventional, single or narrow approaches (Haie, 2020).

A growing and often polarised debate on IE may drive some to question whether to it can or should be used as a performance metric and policy indicator with wide application (ADB, 2017). This question, and therefore this paper, asks; how to respond to the current practice of applying IE to irrigation, basin- and global-scale water policy; an evolution that has moved beyond its original engineering irrigation-system focus. In the face of concerns about this wider application (Perry, 2011; Willardson et al., 1994) a number of trends have contributed to this evolution from an irrigation field and system measure to something utilised more broadly. Put simply, the increasing diversity of issues that irrigation overlaps with has brought in more actors and concerns. These include policy interests in water in basins where irrigation is viewed to have 'spare water' available for reallocation (Deng et al., 2006), and more recently a response to resource constraints via 'climate-smart' precision agriculture (Aisenberg, 2017). In addition, new players not present 20–30 years ago (such as private drip companies and global consulting firms) now use and recruit irrigation efficiency in a strategic sense at the global scale to legitimise policy advocacy (Newborne and Dalton, 2016). Furthermore, an appreciation that scales are useful constructs but overlap continuously and bidirectionally materially, socially and politically (Cash et al., 2006) highlights the question of whether IE is a measure better defined by bounded categorisation (i.e. 'the irrigation system' versus 'the catchment') or by compound, hybrid and fluid characterisation (i.e. irrigation systems nested within irrigated catchments as a joint system).

We therefore argue that it is appropriate and relevant to see irrigation efficiency and its hydrology as important *de facto,* accustomed and useful entry points into a wide range of water concerns. Therefore, our paper is a contribution to a discussion about how best to navigate many applications and perspectives of IE now found at a very wide range of scales by many different actors. However this navigation puzzle requires an integrative 'map' or framework to accommodate and guide current practice. As a response to this need, we propose a framework termed an 'irrigation efficiency matrix' (IEM) which places IE centrally within contemporary water challenges and purposively addresses the 'promises' of IE (referring to expectations of the benefits associated with higher and improving IE) set against its 'pitfalls' (hidden risks, biases, omissions and faultlines associated with not fully understanding IE) and 'paradoxes' (clear contradictions and/or when outcomes materially go against expectations). The backdrop of this paper is therefore the control of water by people, sensors and machines in the multitudinous evolving fields of the world's irrigation systems and how that cumulatively shapes and is recursively shaped by weather, climate and water management in irrigation systems and river basins, in turn responding to powerful corporate, national and international interests.

2. A new 'modal irrigation efficiency' definition

Reframing IE with a framework requires a definition of IE that takes it from being a ratio calculation to being a wider, multi-dimensional guide. Given our proposed IEM is asking 'what is your mode of seeing IE', we suggest the following: 'Modal irrigation efficiency' invites multiple modes of understanding irrigation efficiency arising from different dimensions and cross-scale perspectives on the performant management of the hydrology of irrigated systems and their beneficial consumption of water. This definition broadens IE in a number of ways; IE thus acts as a boundary object (see Appendix A) to invite multi-scale, multi-dimensional perspectives from agronomy, farming systems, engineering, hydrology, business, economics, and the social and political sciences on the hydrology of irrigated systems. This definition retains an emphasis on beneficial evapotranspiration (the numerator in the conventional IE ratio) as a part of beneficial consumption arising from other uses and services of irrigation systems. It refers to IE's role as a performance indicator and introduces the hydrology of irrigated systems, acting as the denominator in the conventional IE ratio. Appendix A provides more definitions including 'irrigated systems' and 'irrigation hydrology', the latter comprising physical hydrology and three types of water accounting.

3. The irrigation efficiency matrix

Supporting the definitions on IE and irrigation hydrology, the irrigation efficiency matrix (IEM) is a conceptual framework which situates ten discursive dimensions of the science, practice and policy of irrigation efficiency within and across five spatial scales that in turn underpin agricultural production, water control, management, consumption and allocation, and that link through to sustainable development goals. We describe its origin, structure and composition before moving on to; a) explore how some of the promises, pitfalls and paradoxes in irrigation efficiency arise from the separations and connections between and across the matrix scales and discursive dimensions, and; b) summarise how the IEM can help users, researchers, policy-makers and others better understand IE to meet societal and environmental priorities. Fig. 1 is the irrigation efficiency matrix, Figs. 2 to 5 provide further detail and explanation of the IEM and Fig. 6 presents an overview of how certain types of pitfalls and paradoxes arise within the matrix. Fig. B1 in Appendix B presents science approaches to the study of IE. Appendix C illustrates the matrix by the application of some worked examples of IE observed by a hypothetical smallholder irrigation system.

3.1. Origins of the irrigation efficiency matrix

The IEM originates out of a number of concerns, including those expressed by irrigation engineers struggling with conventional technical definitions of IE. For example, Hoffman et al., (1990) p 129 wrote; "Irrigation efficiencies can be considered to have a matrix of definitions and values." Furthermore, the IEM is a response to the call for integrative water frameworks by Sadoff et al., (2020); "We urge a rapid change of the economics, engineering and management frameworks that guided water policy and investments in the past in order to address the water challenges of our time" (page 346). In this vein, Sadoff et al (ibid, p 347) are supportive of approaches that promote inclusive dialogue; "water management needs to become better capable of dealing with trade-offs and complexity. Integrated approaches help to identify and minimize trade-offs and unravel unexpected impacts. They also promote inclusive water management, by bringing together different sectors and stakeholders at all scales from local to transboundary".

The IEM draws on Table 1 in Giordano et al (2017), and is constructed by bringing together "multiple scales and dimensions" (van der Bliek et al., 2014) page 11. Regarding scales we accept the utility and convention of creating a tiered system of water management scales (see Section 3.2 for their description). We identify the first three 'lower' scales on the basis of previous frameworks for irrigation efficiency which reproduce engineering-focussed technical conventions for expressing water management at different levels of an irrigation system (e.g. sub-field, field, and the tertiary, secondary and main/bulk canal systems) (BP&A, 1999; FAO, 1999; Jensen, 1983; Reinders et al., 2013). The fourth scale reflects the framing of irrigation efficiency from the point of view of the water management and hydrology of the river basin/catchment (Keller et al., 1996; Seckler et al., 2003; Willardson et al., 1994). Extending these four scales, the fifth 'global' scale features the 'national, international and supranational'. This scale (and indeed all five scales) uses ideas from political ecology and hydrosocial territories (Boelens et al., 2016; Swyngedouw, 2009) to explore how national and global companies and firms, plus trade, virtual water trade and globalisation enrol and recruit ideas of irrigation efficiency to meet an array of strategic interests (Boelens and Vos, 2012; Damonte and Boelens, 2019).

The 10 dimensions draw on existing irrigation efficiency technical frameworks (Hess and Knox, 2013) and from new thinking and debates on water and complex social-ecological systems (SES) from recent decades. Examples of the latter refer to; water-related societal goals and challenges (Rosegrant and Cline, 2003); the scientific framing of irrigation efficiency (Lankford, 2012a); the role of technology modernisation in irrigation efficiency (Lopez-Gunn et al., 2012); the centrality of the idea of 'water saving' to the topic (Batchelor et al., 2014; FAO, 2017); adaptive and compound approaches to managing water (Pahl-Wostl et al., 2008); and an appreciation of multi-variable, cross-scale constituents of socioecological systems (Ostrom, 2007) and how these apply to irrigation systems (Meinzen-Dick, 2007; van Rooyen et al., 2020).

3.2. Five scales of the IEM

In all the Figures, the five scales are the columns. Moving from the lowest to the highest scale, these are; 1) sub-field (comprising individual crops and plants, sub-plots, and single rows and furrows); 2) the field, farm and tertiary levels of irrigation systems, here comprising areas and blocks as well as water distribution and drainage infrastructure and on-farm or small-scale storage bodies; 3) primary and secondary levels of, and whole, irrigation systems, comprising areas and infrastructure for water conveyance, storage and drainage; 4) the catchment, river basin or aquifer, comprising all and groups of irrigation systems and other sectors competing for water, and; 5) national, transboundary-, multi-, supra- and international scales involving a range of interests (e.g. industry, corporate, NGO) interests regarding the irrigated agricultural sector, food chains and water more broadly.

Three qualifications about the use of the term 'spatial scales' apply. First, while we acknowledge Gibson et al. (2000), we reflect the general water literature by employing the word 'scales' to mean levels of the spatial scale. Second, although the five spatial scales appear objectively and hydrologically discrete, they merge into each other or divide into sub-types or can be further defined depending on circumstances such as size and shape, political, historical and geographical convention and the type of irrigation system and catchment. For example, while a furrow or small plot is usually at the lowest end of the five scales, a small rice farm owned by a single farmer and supplied by a single irrigation outlet might be the last unit receiving water with no further activities to distribute this water between individual crops. This proviso leads to the third point; primarily described as 'spatial', the five scales are also institutional and administrative in asking who has responsibilities for water control in that scale.

Drawing on Scholes et al. (2013), scales are vitally important for understanding IE and its complexity (Harrington et al., 2009; Molden et al., 2010) as explained by these 12 considerations:

1. Lower scales are the constituent or nested parts of the next higher scale, and higher scales comprise lower scales. This means that, although there are many times when a single scale provides an appropriate focus to work on IE, an example of 'right-scaling' (Scholes et al., 2013), major IE-related water challenges are best

Five scales → / ↓ Ten dimensions	1 Sub-field (soil, plant, row, furrow, small plot)	2 Field, orchard, farm, tertiary irrigation unit, water storage & drainage	3 Total irrigation system; primary & secondary units, water storage & drainage	4 Catchment, basin, aquifer, multiple irrigation systems	5 Supra/inter/national, trans-boundary basin, irrigated sector, markets, firms
1 **Dimension A:** IE-related water development goals & challenges in each scale supporting agriculture, water, livelihoods & sustainable development	Crop and agricultural production from controlled water placement reflected in irrigation efficiency	Productive farmers/farms via appropriate water control and consumption, alongside other resources (e.g. energy use)	Functioning irrigation systems & ecosystems via controlled water providing equitable distribution of irrigation inflows	Effective water allocation across a basin / aquifer based on control & capping of water withdrawals and consumption in irrigation	Irrigation playing its part in delivery of water-related, sustainable development goals and improved livelihoods, resilience, energy use and market chains
2 **Dimension B:** Stakeholders. People, users and groups most closely aligned with or defined by irrigation efficiency (IE) at this scale	Irrigating labourers, irrigation technicians, small farmers, crop and soil scientists	Farmers and small farmer groups. Supporting services such as agronomists and engineers	Build & operational irrigation engineers. Members/leaders of large farmer groups & water user associations (WUAs). Those providing services for irrigation systems	Basin/water officers. Representatives of sectors e.g. irrigation, urban, hydropower, environmental flows. Operators of larger growers and farm enterprises	Politicians/civil service. Investors: e.g. Govt, ODA, charities, corporates. Firms and services: e.g. drip companies. Lobby groups of sectors. People: e.g. CEOs, auditors, shareholders
3 **Dimension C:** Time frames (timing, time, over time)	Hourly, daily, weekly	Weekly, monthly, crop stage	Crop stage, seasonal, annual	Seasonal, annual	Annual, decennial, longer
	Over time, stakeholders, systems and polices experience weather, climate change, new technologies, new pressures and constraints (see dimension I)				
4 **Dimension D:** Irrigation efficiency motives	Within each of the five scales, IE is defined by and responds to ten 'motives' covering incentives, aims and outcomes relevant for that scale. Within-scale motives are in tension with each other and with motives prioritised in other scales				
5 **Dimension E:** Science approaches to irrigation efficiency	Each scale has its own IE science framing comprising; (mis)understanding, definitions, methods, assumptions, results and goals. Science framing applies to one-off research of systems and to on-going monitoring. Methodologies to encompass the five scales and ten dimensions need to be elucidated				
6 **Dimension F:** Views on irrigation losses, wastes and savings	Because of language, visibility, measurability, scale, and politics, irrigation 'losses' and 'savings' are seen in different ways, and sometimes neutrally, positively or negatively by different actors. Furthermore the language and perceptions on losses are rarely agreed and informed by evidence				
7 **Dimension G:** Views on water redistribution and allocation	Altering how 'salvaged' water moves through irrigation and irrigated basins results in redistribution and allocation of water to four conceptual destinations (proprietor; neighbour; society-economy; nature). Changed pathways often scale-related, legally determined and unique to each situation				
8 **Dimension H:** Views on IE improvement via technology	A 'naturalised' aim to raise IE by improving/modernising irrigation technology is part and parcel of IE but is not straightforward. A bias towards technological pathways to improve IE plays out in different ways across the five scales, with views and opinions co-shaping debates and investments				
9 **Dimension I:** Understanding the wider dynamic context of IE	Seven dynamics create non-linear unpredictable contexts, opportunities and obscurities influencing IE; crop (e.g. crop disease, market swings); irrigation (e.g. spending on rehabilitation); farming (e.g. land consolidation); supply infrastructure (e.g. dams); hydrological/environmental (e.g. soil fertility, drought); human/social (e.g. livelihoods, 'normal behaviours', education); political, legal, institutional & financial (e.g. land/water tenure, political priorities)				
10 **Dimension J:** IE research-policy procurement and leadership	Covers the directionality, leadership and recursive connections, gaps and innovations between IE research and water policy, including research funding, research messaging and other factors. It probes what questions are (not) asked and who is asking them (e.g. policy-makers, donors, farmers & researchers)				

Fig. 1. The irrigation efficiency matrix with five scales and ten discursive dimensions.

served when all or many of the five scales are accommodated together (multi-scaling) or because one scale strongly influences IE in another scale (cross-scaling) as happens in the iterative and recursive connections between water consumption in irrigation systems and water availability and allocation for the river basin.

2. Higher scales divide water to two or more units within a lower scale which determines water outcomes of distribution, efficiency, productivity and equity (Lankford, 2006, 2012a).
3. Thus, scales 1 to 4 can be seen as a microcosm or fractal of each other because of the way that water has to be similarly accessed, stored, conveyed, divided, depleted and consequently resolved (or disposed of) either within each scale or to the next scale above.
4. Actors associated with each scale have valid but different set of IE 'motives' (discussed below).

5. As explained later, pitfalls and paradoxes arise when IE perspectives and motives relevant to one scale are (mis)applied to other scales, or are not applied to other scales when they should be.
6. Although provisos apply (see below), the irrigation efficiency ratio within each scale can generally be conceptualised (but not necessarily experienced or managed by users) via the assessment of the IE hydrological balance of inflows and outflows of water in that scale.
7. However, when defining what is a 'loss' within IE, reference should also be made to the hydrology of the lower and higher scales that encompass that scale (Scott et al., 2014) and therefore to the nested character of irrigation hydrology. Thus water 'lost' to a field in scale 2 might be picked up by farmers on a downstream irrigation system and therefore is 'paradoxically not lost' with respect to scales 3 and 4 (also see discussion below on losses).
8. Nevertheless, the previous point must also be qualified on the understanding that water lost within a scale may be lost to others irrigating in that scale and therefore still represent a genuine 'loss' of water volume and in irrigation timing (Lankford, 2006). In other words, water lost to a field in scale 2 is also lost to neighbouring fields sharing a networked irrigation supply on a shared canal/drain system unless farmers pump water out of the drain or aquifer.
9. Following the previous two points, although IE in the five scales might be seen as primarily *hydrological,* this is not always a wholly accurate, useful or practical way of managing water, land, technology and other inputs. For example, scale 1 (the sub-field unit of crop, row and small plot) is subject to agronomic interests while scales 4 (basins) and 5 (national and international) view IE via social, political, economic and corporate objectives. Other scales are associated with other ways of experiencing and measuring IE – for example in scales 2 and 3, water managers look for proxy indicators of IE such as timing, soil moisture readings, visual observations or area irrigated from one season to another. Thus, irrigation efficiency in these scales can be experienced and understood differently than by computing a hydrological balance.
10. IE has to be interrogated by the challenge of 'out-scaling' – in other words how to measure and manage available water for crops and fields (in Scales 1 and 2) not just for one field of, say, 0.1 ha, but for thousands of fields across a catchment (Green et al., 2010) or not just one river basin (scale 4), but all river basins nationally or globally.
11. It is the 'reach of scale' from scale 1 (an individual plant or row) to scale 5 (national and international levels), embracing diverse actors and motives, that explains the difficulties of harnessing IE for narrow or simple purposes, and whether 'irrigation efficiency' remains an appropriate term for research and policy discussions across all scales.
12. Related to previous points, moving across the scales brings methodological changes, data uncertainties and difficulties in accommodating changing motives for using IE. For example, historical and relatively coarse IE and WP results derived by satellite methods applied to irrigation systems and river basins (scales 3–4) need to be reconciled with different results from fine-grained field-level assessments (scales 1–2). Furthermore, while recognising the considerable advances made in the last decade (Babu et al., 2012; Piedelobo et al., 2018) satellite data will be less useful to farmers managing their daily/weekly water in scales 1–2. The topic of research for each and all scales is picked up elsewhere in the paper.

3.3. *Ten discursive dimensions of the IEM*

To invite different interests and actors to IE discussions and to elucidate the promises, pitfalls and paradoxes that arise within and across the five IE scales, ten 'discursive dimensions' are conceived and discussed. The dimensions represent the 'rows' within the IEM (Fig. 1). They are; A) IE-related water development goals and challenges in each and all scales in different locations; B) people associated with each scale; C) time-frames; D) multiple motives behind IE; E) science approaches to IE; F) views on irrigation losses, wastes and savings; G) views on water allocation connected to IE; H) perspectives on improving IE via technological change; I) understanding the wider contextual dynamics that IE sits within, and; J) innovation and leadership shaping the procurement of IE research for policy.

The ten dimensions show how farmer and public opinion, management, science and policy are debated and structured within and across the five IE scales. Being 'discursive', the choice and explanation of the dimensions may be interpreted differently by others, a point which expounds the contentious nature of IE and suggests that an objective science that measures and informs IE and its associated water challenges is elusive. Thus, although the arrangement of the ten dimensions suggests a logical order (rather than as a heuristic architecture to think about IE), in reality viewpoints and influences on IE can arise in any order and from any source. It is these various competing and rarely cross-checked entry points to IE that help produce its associated pitfalls and paradoxes. For example, policy-makers with little irrigation experience might instinctively view precision irrigation technology (in dimension H) as a way to 'save water' (dimension F) but poorly articulate how these savings reallocate water (dimension G), deliver better performing irrigation that aligns with specific IE motives (dimension D) and serve major water development challenges in dimension A. The ten dimensions are now discussed in greater detail.

Dimension A: IE-related water development goals and challenges. The five IE scales determine how water use and management underpin, and respond to, different goals and challenges of agricultural production, livelihoods, ecosystem services, water allocation, systems resilience and sustainable development. Dimension A (Fig. 1) presents these water development challenges. The lower two scales (crop, field and farm) are associated with crop production (with cumulative effects on food security at the higher scales); scale 3 with irrigation management and equitable distribution of water withdrawals and consumption (again supporting policy in the next higher scales), and; the higher scales 4 and 5 with water allocation to meet and buttress resilience, environmental and sustainable economic and development goals, and viable market chains.

Dimension A is not simply about fitting scales to challenges and watching the pieces fall into place. Rather the challenge of governing irrigation performance in irrigated river basins is manifest in dimension A; how, in the face of many water-related priorities, IE responds to. delivers or fails to deliver trade-offs between food production, energy use and the intersectoral allocation of water (Vos et al., 2019) across the five scales (Harrington et al., 2009; Scott et al., 2014). It is because IE cannot automatically, naturally or simply advise on these challenges that new ambitious IE research is required, a priority returned to in Dimension J.

Dimension B: Associated people. Dimension B associates five groups of people, stakeholders or actors with the five scales. The groups and their respective scales are; 1) irrigation labourers, field technicians and crop and soil scientists; 2) farm-owners, small farmer groups and agronomists; 3) larger farmer groups, growers and cooperatives as well as large irrigation system owners, and irrigation and water infrastructure engineers and related services; 4) basin and ministry water managers responsible for water allocation, plus representatives of, and companies servicing, sectoral interests (e.g. agricultural, urban and environmental), and; 5) politicians, policy-makers, investors, corporates and lobby-groups (e.g. a farming lobby) with interests in irrigation and river basin water expressed at the generic, value chain, sectoral, national, transboundary and inter-/supra-national scales. Clearly this is a simplification not only of the relationship between scale and stakeholder but of the recognition that; a) stakeholders can be members of more than one scale-related group implying a risk of conflicts of interest and/or policy capture; b) new types of actors enter the debate on IE over time (e.g. companies concerned with their water footprint), and; c) scientists can align themselves with one or more actors and communicate messages on their behalf (also seeking influence over IE debates). For these reasons the specification of stakeholders and their messaging commonly need verifying from on-the-ground study.

Connecting 'people' to irrigation efficiency in dimension B invites a discussion about those who materially affect irrigation activities versus those who politically shape change in this domain. In addition, analogous to a pyramid, the numbers of people engaged in each scale change. In the lowers scales there are many thousands of irrigators controlling water on their farms, while at the higher basin and national and international scales there are fewer people materially engaged in managing IE. This generalisation needs to be qualified if and when staff in many organisations in the fifth uppermost scale hold influential views on IE that shape national and global debates on irrigation.

Dimension C: Time frames. The IEM hypothesises that the five spatial scales are aligned broadly with different time-scales and time frames connected to agronomic, system and stakeholder interests. These range from short time steps (hourly, daily, weekly) at the lower sub-field and farmer scales, to annual and longer time periods associated with policy change at the basin, national and international scales. Thus, time frames are important in understanding the various IE motives (see below) typified by farmers wishing to 'top up' soil moisture within a 5–15 day period as compared to basin managers seeking 12-month accounts of basin-level hydrology. In addition, all five scales sit within longer trends and cycles, exemplified by the slow build-up of salts in irrigated soils which impacts farming in scales 1 to 3, or climate change which arguably applies to all scales in different ways. Furthermore, dimension C acknowledges that all five scales and their respective time-frames are subject to weather and climate seasonality and variability, seen in time spans that last about 2–8 months. For example, farmers in scale 2 managing water on a daily or weekly basis and basin managers in scale 4 managing water on a weekly to monthly basis will both act differently in a drought lasting half a year.

Dimension D: Irrigation efficiency motives, aims and outcomes. Irrigation efficiency, and how it supports irrigated agriculture, water allocation and development, can be understood by exploring what irrigation efficiency and associated IE technologies are attempting to 'promise' and reveal. In short, dimension D is about the interests in and motivations behind usages of IE. To elucidate this, and accepting these are interpretable, Fig. 2 presents ten entry points, termed 'motives':

1. Design; IE informs the choice, type, design and sizing irrigation infrastructure and technology (FAO, 1999) including natural components such as soil–water infiltration rates and moisture availability. (Irrigation technology is revisited below in dimension H).
2. Operation and maintenance of infrastructure; IE and associated measures of water control inform or indicate the operation and maintenance of individual systems or parts thereof (FAO, 1986; Lankford, 2006). In other words, system irrigation efficiencies arise from the 'accurate' operation of well-designed and maintained irrigation technology.
3. Hydrology, water allocation and quality; changes to IE bring shifts in surface and subsurface water flows, volumes, pathways and salts (or effluents) through and from an irrigated system (Karimov et al., 2012; Molle and Tanouti, 2017; Ward and Pulido-Velázquez, 2008).
4. Cropping, soils, agronomy, farm production and farming systems; covering how and why IE connects to soils and field management, supports decisions on crop patterns and production (Karrou et al., 2012), responds to farming and technological innovation, reacts to drivers such as higher labour costs (Mintesinot et al., 2004; Senyolo et al., 2018), and fits or clashes with farming systems and livelihoods (Guijt and Thompson, 1994; Woodhouse et al., 2017).
5. Biodiversity and other resources; how IE relates to and influences ecosystem services (McCartney et al., 2019) and other/nexus-type inputs or outcomes e.g. energy (Jackson et al., 2010).
6. Economic; affecting all ten IE motives is an economic underpinning whereby material changes are incentivised and delivered in an economically efficient sense and are therefore influenced by costs, prices and subsidies for water and technologies (Cai et al., 2001; Scheierling et al., 2006), alongside the benefits of water investments and institutions such as markets (Garrick et al., 2009; Gómez and Pérez-Blanco, 2014; Ward, 2014).
7. Social; affecting all other motives and covering a number of aspects such as; the subjective and social nature of seemingly objective loss fractions (Cantor, 2017); a local social characterisation of irrigation efficiency (e.g. tail-end paddy rice farmers in southern Tanzania pointing to above their ankles indicating that they believe top-end farmers are storing too much water in their fields, water they say should cascade through the irrigation system to their location), and; an appreciation of the social, relational and farming transformations wrought by IE changes (Lopez-Gunn et al., 2012; Sese-Minguez et al., 2017; Trottier and Perrier, 2018; Venot et al., 2017). This motive is also where IE can be interrogated via wider lenses of irrigation geographies, histories, cultures, landscapes and agrarian change (Bolding et al., 1995; Zimmerer, 2011).
8. Political, strategic, managerial, administrative, financial and developmental; IE informs a high-level comparison of the management of systems over space and time, for example for operating farms in scales 2–3 (Benouniche et al., 2014; Harrington et al., 2009). This motive also covers how, scientific ideas are recruited and political alliances, new markets and subsidies are leveraged most often in scales 4 and 5 for investment and strategic purposes, (Trottier and Perrier, 2018); or how development projects in higher scales should recognise current trajectories of managing water in both irrigated and rainfed agriculture (Hope et al., 2008).
9. Learning and intermediary; IE is employed as a boundary and/or intermediary concept to enhance learning, putting farmers and others at the centre of IE changes (Benouniche et al., 2014; Knox et al., 2012) and to discuss efficiency, technologies and management (Fielke and Srinivasan, 2018; Levidow et al., 2014; Srinivasan et al., 2017).
10. Effects on resilience; whether raising irrigation efficiency, and the consequences of that change, confers or undermines resilience (Molle and Tanouti, 2017; Scott et al., 2014).

Three points relate to these 10 motives. First, we argue they reveal the considerable difficulty of discussing the purposes of IE – for example how different actors might latch onto one motive while dismissing the significance of other motives. Second, discussed below, and referred to in Fig. 6, we argue that the 10 contrasting motives (and their sub-types) in dimension D located across the five scales are responsible for generating a number of IE pitfalls and paradoxes. Third, although we believe all 10 IE motives are relevant, we foresee how stakeholders might usefully concentrate on a small number to manage water and raise performance (Reinders et al., 2013).

Dimension E: Science approaches to irrigation efficiency. Dimension E (Fig. 3) supported by Appendix B expresses how irrigation efficiency should be seen via a range of concepts, calculations and methods based on different definitions, and computations enabled by particular technologies such as flow meters or satellite images. Dimension E therefore allows us to make the following seven observations:

Five scales → / ↓ 10 IE motives	1 Sub-field	2 Field, farm, tertiary irrigation unit	3 Irrigation system	4 Basin, aquifer, multiple irrigation systems	5 Global, national, sectors, firms
1 Design of infrastructure	Type, design, sizing, construction of fields and irrigation infrastructure iteratively matched to farmer, crop, soil, rooting depth, land slopes, climate, hydrology, catchment and environment within these three scales			Inter/national influences on design options; predominant schools of design; pricing; training; comparative research	
2 Operation & maintenance (O&M) of infrastructure in face of water variability over time and space & rules of use	Control/matching field inflows to crop transpiration. Refill & manage soil-root reservoir over time/space. Control water along row or over field to individual plants. Maintain soil & infrastructure to ensure this. Responding to weather, rainfall events and drought	Field control of water to distribute water around farm and rotational group. Timing control within crop season and start and end of season. IE via direct or proxy measures (e.g. leaks, uniformity, adequacy) informs O&M	Supply, division and distribution of bulk water to match demand of tertiary and secondary units. In this scale, cyclical effects more pronounced; delayed over-irrigation versus timely accurate doses. Managing droughts	Opportunities for adjusting & capping withdrawals at main intake level to match within-system operation or basin needs. Responding to changing demands for basin water and climate change. Fitted to storage options	Sustainable productive irrigation systems support delivery of sustainable development goals (SDGs). Long term climate, economic & infrastructural trends that affect/use water
3 Effects on irrigation hydrology; water consumption, redistribution allocation and quality	A reduction in the amount of water needed at the crop and furrow edge is achieved if transpiration remains the same and field losses (runoff, seepage or evaporation) are reduced. Some or all of these losses may switch to transpiration and greater consumption	Options; A) faster rotation of water due to reduced losses; B) reduced (forestalled) water deliveries to fields as a result of reduced losses; C) distribution of these 'savings' up a scale or to other units laterally within this scale; D) greater transpiration from other crops	Options: A) 'Saved' water 'banked' in storage, rivers, aquifers; B) 'saved' water to greater consumption via command area, crops with greater transpiration & increased cropping intensity; C) return flows recovered and reused	Options: A) Forestalled irrigation water allocated to storage or other irrigation systems & sectors; B) Higher irrigation water consumption; less allocation; expansion of irrigated land area. Return flows from irrigation results in poorer water quality for others	Food production. Water allocation. Managed water footprint and reputational risks of food chains. Sustain freshwater ecologies. Risk of varied outcomes if IE not understood – e.g. less water for domestic and urban growth
4 Cropping, soils, agronomy and farm production	Higher farm yields via improved water timing, dosing, duration and placement over space. Reduced nutrient loss. Better growth from less crop stress & denser more uniform canopy. Changes to crops/varieties, cropping intensity/area. Optimal, deficit and protective irrigation (against drought failure). Irrigation effects on pests & diseases, soil salts and orchard/soil temperature. Changing costs of labour, agro-chemicals & mechanisation			Consequences for national/global food chains, firms, production and prices from changing crop patterns, yields and area of irrigation	
5 Biodiversity & water-energy-food nexus	Lower or greater water consumed: effects on other ecologies & crops in systems; e.g. wetlands, fisheries and canal-side trees. Energy for irrigation; energy infrastructure, price subsidies, skills & maintenance			Nexus (e.g. electricity) costs. Changing water flows & timing for whole basin ecosystem services and freshwater ecologies	
6 Water and irrigation economics	Affecting all motives at all scales, IE intersects with water & irrigation economics: e.g. cost-benefit of irrigation rehabilitation; costs, sales and subsidies of technologies; job per drop; rebound effects; water pricing and trading related to markets; demand elasticity; economic diversification underpinned by changes in water allocation and water quality				
7 Social framing/ undertstanding	Affecting all motives at all scales: 1) IE, losses and savings are subjectively and socially defined; 2) Materially and by opinion, IE & losses connect people; 3) IE technologies bring social changes; 4) Each person holds own IE views; 5) IE qualitatively (mis)characterised; 6) IE and irrigation geographies, histories, cultures, landscapes & agrarian change				
8 Political, strategic, governmental, developmental	Systems management and administration. Group knowledge & concerns met over time and space. Conflict between farmers. Relative performance over time. Comparisons between farmers and between system types (e.g. drip vs canal). "Use it or lose it" efficient use to protect licences. Land expansion, retirement & fallowing			Supra-/inter-/national/corporate strategies to manage footprint, reputation & risk. Influence debate, access drip investments, sales & subsidies. Design development projects. Voter patronage	
9 Learning and mediation	IE requires social inquiry & mediation; IE is an intermediary boundary concept to help farmers learn and co-manage irrigation systems and technological change				
10 Resilience	Emerging and possibly contradicting influences between IE and resilience at all scales covering strength and direction of connections (e.g. positive, negative, long-term)				

Fig. 2. Dimension D; framing irrigation efficiency as ten motives across five scales.

1) Methods for measuring and formulating IE should relate to scale and the motives given in dimension D (Green et al., 2010). For example, the determination of classical irrigation efficiency appropriate for irrigation systems in scale 3 would not be suitable for scale 4.
2) Each of the five scales may have more than one method with its own disciplinarity, terminology and calculus of IE. For example, in scales 3 and 4, IE can be calculated from hydrological and meteorological data taken at various locations in a catchment, or be imputed from crop patterns taken from satellite imagery (Bandara, 2003).
3) Methods, either being building blocks of other methods or proxy measurements, do not always coherently result in an 'IE ratio' or a ratio that can be verified by a hydrological balance. (For example, in scales 1–2, associated measures of water control such as the uniformity and adequacy of irrigation down a furrow or in a field are best analysed by examining patterns of soil wetting or crop growth. Furthermore, irrigation uniformity needs to be connected to IE for the way in which over- and under-irrigation/wetting affects rates of beneficial evapotranspiration and the magnitude and types of other 'losses').
4) Within scales, methods may compete with each other for their history and recognition, and their utility and ease of application.
5) Determining IE in any one scale should ideally triangulate with methods drawn from other scales.
6) Scaling-out methods to manage IE might be achieved by multiplying a given technology (e.g. employing thousands of soil moisture sensors at the field scale) or by considering IE at the next scale up (e.g. by imposing a lower water duty on the whole irrigation system).
7) Assessing IE and types of losses faces significant gaps in locating robust reliable hydrological and irrigation data in all scales (Simons et al., 2015).

The above seven concerns are addressed when re-evaluating IE via 'research methodologies', a topic expressed briefly in the bottom six rows of Fig. 3. This argument arises out of an understanding of the complex systems character of IE, how it acquires strong social and political norms and interpretations, and how it changes in behaviour and relevance over time and space. Accordingly, there is a need to identify coherent methodologies for each of the five scales as well as wider IE methodologies that encompass two or more scales. For example, in scale 4 the use of satellite imagery to derive basin water accounts (Simons et al., 2015), differs methodologically with an engineer's computation of IE in scale 3 arrived at by multiplying estimated efficiencies of different parts of an irrigation system (Lankford, 2012a) (see Appendix B), which in turn differs methodologically with the study of IE from the hydrological accounts of irrigation systems in scale 3 (Reinders et al., 2013). Furthermore, a methodology approach makes it possible to employ a political-ecology type lens to explore the problems associated with a given irrigation priority (e.g. to raise the performance of national public-sector irrigation schemes) by looking its attendant IE scale, stakeholder-group, motive, method, measurement apparatus and data-set (Van Halsema and Vincent, 2012).

Dimension F: Views on efficiency losses, wastes and savings. Some of the most intractable debates associated with understanding IE have been related to the nature of irrigation losses, and views on how they may be reduced, with the understandable but often not correct assumption that reducing losses implies 'saving water' (FAO, 2017). This topic has seen much deliberation (Batchelor et al., 2014; FAO, 2017; Frederiksen and Allen, 2011; Frederiksen et al., 2012; Grafton et al., 2018; Seckler, 1996; Ward and Pulido-Velázquez, 2008) and requires further substantial treatment than can be given here in order to understand the promises, pitfalls and paradoxes in this contested space. The aim of this paper is not repeat these debates or to reaffirm that (mis) perceptions on losses, wastes and savings can be addressed by improved accounting and terminology (Perry, 2011). The IEM in Fig. 4 allows us to present a number of views on this problematic, starting at the top with questions that illustrate types of 'views' on losses associated with the five scales.

We discuss here some considerations which, given the heterogeneity of irrigation systems, mean that the types of losses, and their effects, reduction and relationships to IE, cannot be easily defined. Thus, because irrigation losses and their pathways are unique to a given location, scale and moment in time, generalisations about the nature of losses (for example that most return to the basin) are not always accurate.

- One hydrological complication is that a 'loss' for one use, actor, or scale, may be the input for someone else laterally within the same scale or may be recycled to a higher scale (Scott et al., 2014). Thus, terms such as 'loss' and 'waste' can only be accurately defined when the boundaries of the relevant spatial and time scales are specified. However, boundaries between spatial and time scales, being fluid, flexible 'ad hoc' and sometimes institutionally rather than physically defined, are often not easy to demarcate 'in the field'. It is this problem of definition of the boundaries within and across scales that partly explain the paradox that reducing 'losses' at one scale (e.g. field) can increase consumption at the basin scale (also seen in the situation is when drip irrigation is used to "conquer the desert" (Vos and Marshall, 2017)).
- Losses are not always visible as seepage and drainage flows from fields. On the contrary, the split of irrigation water between non-beneficial evaporation (a 'loss') and beneficial evapotranspiration is extremely difficult to discern and measure. To explain this, we start with the observation that crop growth is dented when irrigation scheduling is poorly timed (late-arriving). If this happens often during a crop's season, leading to widespread poor growth, more irrigation water will be 'lost' as non-beneficial evaporation from soil surfaces sitting between thin and patchy crop stands or as not-highly productive transpiration from stressed and under-sized leaves. This situation contrasts with 'on-time irrigation scheduling' leading to higher beneficial transpiration from a full and healthy crop canopy. A generalisation problem arises because, while a whole field of highly wilted crops is relatively easy to spot, the usual distribution of crop stress (and the division between beneficial evapotranspiration and non-beneficial evaporation) over space and time is heterogenous, ephemeral and gradual.
- It is also difficult to discern the pathways taken by recoverable and non-recoverable flows (Simons et al., 2015) when irrigation water moves out of the root zone as seepage and drainage. These two dispositions are defined by which 'physical flow losses' are returned to the basin for further use. But this teleological definition hides an empirical mechanistic understanding of irrigation hydrology and what factors and processes cause these dispositions. In addition, these two pathways are not easily observable or measurable taking place via soil–water and groundwater movement. Neither are they clear-cut in terms of their benefit; drainage might be recoverable but carry more salts or be slower moving compared to water that would have stayed in a river had it not been diverted via an irrigation system.
- Accounting of water via fractions (beneficial, non-beneficial, recovered, etc.) does not easily guide irrigation managers who view their performance in other practical and vernacular ways. For example, managers are concerned to use canal 'flows' to cover a given command 'area' with its correct 'dose' in a 'timely' way, four factors that combine to throw a light on irrigation efficiency (Lankford, 2006, 1992). In a second example, losses change from being visible to being less visible, or from place to place, or from one person's responsibility to another's. Thus an irrigation canal full of weeds and silt might have its flow throttled back to reduce daytime canal spillage losses, but this leads to slower completion of its command area and to operational leaks occurring at the end of the canal during night-time. In another example, managers might not be sure whether they are 'under- or over-irrigating'. The latter concern is surprisingly

Five scales → / Factors ↓ (See Appendix B)	1 Sub-field	2 Field, farm, tertiary irrigation unit	3 Irrigation system	4 Basin, aquifer, multiple irrigation systems	5 Global, national, sectors, firms
Example definitions of IE	Sub-field IE, supported by uniformity study. Biological crop water use efficiency (WUE)	Tertiary and field efficiency; timing, depths of water	Classic efficiency, IEc, for the whole irrigation system	Effective efficiency, IEe Water accounting (WA) of fractions	Economic efficiency. Water footprints. Basin and national WA
Relevant ratio	IEc = ETb / Supply to sub-field. Yields / water use	IEc = ETb / Supply to field or tertiary unit	IEc = ETb / Withdrawals into irrigation system	IEe = ETb / Depleted by irrigation system	Averaged statistics or rapid 'audits' of proxy indicators
Main calculus method(s)	Agro-met transpiration/ and water inflows. Uniformity methods	IEc = E3° x Efield	System level factorial calc: IEc = E1° x E2° x E3° x Efield	Areal calculation of Eto as proxy for depletion	On-line resources and data calculated, triangulated
Study equipment & methods	Yield sampling; lysimeters; Crop & soil instruments; scheduling	Water balances in/outflows; timing measurements	Flow measurement in different parts of system	Satellites; withdrawals; hydrological and meteorological data. Questionnaires	
Associated measures	Timing/IE/area/flow calc: IEc = (mm x ha)/(l/s x hrs x 0.36). IE as relative = (system A/system B). Relative water supply (RWS). Measures of equity and uniformity; adequacy of supply			Irrigation hydrology gains appropriation	On-line databases e.g. water
IE monitoring & management methods and technology	Irrigation scheduling; yields; unit-level water inflows and outflows; soil-wetting pattern tests; sap-flow and infrared-observations of crop stress; soil moisture sensors		Command area covered; adequacy; uniformity, timing.	Satellite records; irrigation withdrawals; hydrology.	Summarised stats of farm, system and basin data
Other studies	Satellite based services; drone, smartphone. Days moisture stress. Measure relative changes rather than absolute soil & crop moisture. Salt balances; drainage & leaching needs		Areal and timing comparison. Satellite monitoring	Adding economics and finance to the water studies. Researching and benchmarking across different irrigation systems and basins. Summarised stats of farm, system and basin data	
Main data problems & risks	Informal farm records; Costs of monitoring at small scale; data retention & analysis not easy	Observational or little data on water management	Abstraction and flow data often missing. Assumptions feed design procedures	Streamflow and demand data often missing. Reliance on satellite data and assumptions	Reliable robust data often missing. Based on assumptions or modelled WA
Individual systems	From a science point of view, IE sits in a wide variety of unique irrigation and basin/aquifer 'systems'. E.g. types of drip/sprinkler/gravity water control; distribution of sizes and areas under irrigation; top/tail differences; soil/slope/land; climate/agrometeorology; surface/groundwater access & connectivity; water quality				
Changeable systems	Dimension I notes that IE sits in highly changeable natural, human, physical and economic environments. From a science point of view, this makes it difficult to control conditions and variables wherein IE interventions and impacts can be easily measured, isolated and ascertained				
Language of IE & social inquiry	"Water level in rice plot is too deep, above ankle"	"I've reduced runoff visible in drains"	"Without rain, unable to cover whole area	"Rivers dry-up below irrigation"	"Traditional use of ditches" "Farmers waste water"
IE social science	IE and its science as a socially mediated discussion/discourse via many lenses: e.g. political ecology; socio-ecological systems (SES); Science, technology, society (STS)				
Disbenefits; poor, biased or no IE science	Farmers remain with or change their practices without information or test new technologies but are unable to systematically compare like with like. Farmer-led IE improvements not captured by research		Irrigation interventions have no or sub-optimal effect on IE and irrigation hydrology	Irrigation interventions raise water consumption. IE assumptions continue. WA unable to guide policy. Case studies (e.g. Murray-Darling) dominate rather than assist wider thinking	
IE as methodology	Each scale can be considered via methodologies relevant to that scale; also all five scales encompassed by one or more methodologies. Also: What methods in each scale support rapid assessment 'at scale'? How do methods incorporate information from the level below and support the next scale up?				

Fig. 3. Dimension E; framing the science of irrigation efficiency as methods and methodologies.

difficult to distinguish since both harm crop growth. Incomplete irrigation scheduling records and rainfall events (happily) disrupting a regular order of irrigation further confuse this question. Or, in an additional complication, field application efficiencies can be high (as can happen in both canal/gravity and drip systems detected by uniform crop stands, very little runoff and shallow soil wetting fronts) but the design and operation of the supply network dictates an uneven division of 'specific water to area' in litres/second/hectare (Lankford, 1992). If this water distribution does not closely match crop needs (or is otherwise not compensated for) then fields and farms become cumulatively under- and over-supplied, leading to the risk of a lower (classical) irrigation efficiency and to an increase in different types of losses.

- With 'losses' comprising part of the denominator in the irrigation efficiency ratio, also comes the assumption that we should find it easy to know the total denominator; the water withdrawn into an irrigation system (in classical IE terms). But this is extremely difficult to know because unevenly distributed rainfall events introduce complicated inputs and outputs and because farmers often draw on many types of unmeasured water supply including shallow soil water tables, groundwater and recycled water (Ortega-Reig et al., 2014).
- Furthermore, flow data on water supply, withdrawal, consumption, distribution and losses at all scales are worryingly scarce leading to approximate water accounting.
- Referred to in dimension I, irrigation and rivers basins sit within highly variable environments and contexts, making the statistically valid comparisons problematic. In other words, changes in streamflows may be due to non-irrigation catchment changes (van Dijk et al., 2006), a topic revisited below.
- Closely connected to the difficulties of the technical measurement of losses and savings, are scale-, system- and time-determined human and social perspectives on these issues. Thus, a farmer in scale 1 working with a given volume of water at the field edge is concerned with 'reducing losses' in order to stretch out this available water to her existing crop when this supply further tightens as a result of drought or rising competition from other farmers. But the same farmer as a part of a group of farmers in scales 2 and 3 might be interested in reducing irrigation losses in order to expand her irrigated area in the next 2–3 years. These multiple simultaneously held perspectives on 'losses and savings', make agreement on cross-scale definitions extremely difficult, especially if that discussion is being driven from one scale and its set of motives (e.g. water savings and allocation in scale 4).
- Related to the previous point, pitfalls occur in the use of words like 'losses' and the provenance of that language. While it is one matter for irrigators familiar with their neighbours (scales 1 to 3) to use extant vernacular such as "they waste water", this does not excuse policy makers and professionals situated in scales 4 and 5 to use such terms without respect for the consequences of misinterpretation (though such language is employed at these higher scales for political and strategic purposes (Boelens and Vos, 2012; Trottier and Perrier, 2018).
- Scientists should be wary of over-generalising that a switch in technology from gravity/channel irrigation to drip results in a Jevons type rebound in water consumption at the basin scale 4. This view only holds if the following generalisation is correct; "Hydrology demonstrates that excess water applications do not "disappear". Even when some bare-soil evaporation occurs, most excess water returns to the groundwater or surface-water systems for re-use" (FAO, 2017), page 35). This generalisation should be questioned because of the great variety found in, and relative significance of, the many variables involved in the hydrology of irrigation systems and the environment/catchment they sit in (such as irrigation design and operation, cropping patterns, agrometeorology, slope, soil type, geology, etc. For example, a flooded bunded bare rice field underlain by a clay soil with a seepage rate of 2 mm/day will witness a potentially recoverable fraction that is one-quarter of 8 mm/day evaporation losses. Put another way, some gravity/canal irrigation systems have genuinely low efficiencies whereas other systems, responding to internal water competition and scarcity over many years, perform at much higher efficiency. It is not only that losses are quantitatively larger in the former, but that losses are of a different and forestallable type. Observations by authors of this paper of large-scale irrigation systems in Northern Nigeria and Pakistan indicate considerable leakage to non-recovered losses in local sinks (although minor swamps and wetlands bring other benefits) and to evaporation because of poorly scheduled irrigation. Improving efficiency in these genuinely inefficient systems would not necessarily result in more consumption at the field, system and basin levels because the gain in crop transpiration would come from losses that were not beneficial or being recovered by local or downstream farmers or to the basin.
- Thus, given the above points and that the seemingly objective quantification of a loss is determined by a highly variable context, it is perhaps more sensible to view losses as subjective, value-laden and relational (Cantor, 2017).

Dimension G: Views on water allocation connected to IE. Acknowledging a large subject area, the bottom panel of Fig. 4 introduces how 'saving/salvaging' water losses (in dimension F) connect to hydrological outcomes and their significance for water distribution in scales 1–3 and allocation in scales 4 and 5). Lankford (2013) refers to a commons of salvaged resources to be freed up by efficiency gains as a 'paracommons'. He specifies four conceptual destinations for the redistribution of savings/salvages; the proprietor making the savings; an immediate neighbour of the proprietor (e.g. an irrigator sharing a distribution system or using water draining from an irrigation system); the wider economy, and; nature or environmental flows. Four examples of complications illustrate that it is not easy to re-allocate savings; 1) the difficulties in transferring of volumes and flows from where consumption is reduced to new destinations; 2) addressing the (dis)incentives that influence reallocation, for example irrigation licences often give abstractors the right to use their own 'losses' (Norris, 2011); 3) the difficulties in addressing material savings via 'commons' type institutions, fora and thinking (Lankford, 2013), and; 4) explicitly creating safeguards to allocate water savings arising from many small-scale and dispersed sources (Batchelor et al., 2014).

Dimension H: Views on IE improvements via technology. A key mechanism through which actors develop views on IE is by their understanding that types of irrigation technology are 'efficient' or 'inefficient' (Boelens and Vos, 2012; Lankford, 2012a). For example canal/surface irrigation is often viewed as being traditional and inefficient while so-called 'modern' or advanced sprinkler and drip irrigation technologies offer higher efficiencies (van der Kooij et al., 2017). The top half of Fig. 5 introduces these views via several scale-related contestations and pitfalls. For example, farmers in the lower scales, more familiar with irrigation water control, have considerable practical experiences that require careful observation and that make it difficult to conclude on the binary 'efficient/inefficient'. This flexibility contrasts with convictions held by higher scale actors often lacking a deep or practical understanding of irrigation. Related questions include how to improve canal/surface irrigation without switching to drip and sprinkler systems (Sese-Minguez et al., 2017) that require more energy, equipment, expertise and associated investments, to say nothing of the changes to cropping and management and the 'atomization' and breakdown of common-property norms that characterize many surface irrigation systems (Ortega-Reig et al., 2017; Sese-Minguez et al., 2017).

Dimension I: Understanding the varying and dynamic context of irrigation efficiency. In the lower panel of Fig. 5 seven factors explain the highly dynamic context which shapes IE and the people and programmes working on IE. These include; 1) crop and cropping systems; 2) irrigation systems; 3) farming systems; 4) water supply infrastructure; 5) meteorological, hydrological and environmental; 6) human, education

Dimension F: Views on irrigation losses, wastes and savings

Five scales → / ↓ Factors	1 Sub-field	2 Field, farm, tertiary irrigation unit	3 Irrigation system	4 Basin, aquifer, multiple irrigation systems	5 Global, national, sectors, firms
Illustrative questions or statements)	"I can / I cannot realise those leaks and losses?"	"Why do my neighbours waste water?"	"How much water does this system leak or lose?"	"Canal systems and farmers waste water". "Raising efficiency leads to a Jevons rebound in water consumption"	
Perceived fates of losses	Beneath root zone or at end of field	Held on land / in soil; as visible spillage and leakage	If compensated for by design then of reduced concern?	Losses returned downstream and the basin by return flows	Losses are wasteful and to be reduced
Example flaws of these perceptions	Often fails to see invisible non-recovered evaporation losses	Sees IE locally; does not see total irrigation system or basin-wide	Not see losses recovered within or below system	Not see multiplicity of hydrology pathways for losses	Without evidence "all canal systems inefficient". Language imprecise
Sources of perceptions	Daily management of visible *in situ* losses	Shaped by location of farmer on system	Shaped by training of engineers	Widespread narratives of low irrigation efficiency for policy, sales and investment purposes	
Costs and consequences of these perceptions	Improvements to water control are not implemented. Growth impaired esp. critical plant stages	Losses not recycled or retained in farmer group; poor timing & productivity	Varied over time/space: Poor timing, poor equity, reduction in productivity	Recovered losses take time & cost; Non-recovered evaporation losses not identified/low concern	Differences between fates of losses are generally not well understood
Yet other utilities of losses	Picked up within the field elsewhere; controlling soil & canopy temperatures	Delivering ecosystem services & buffering against shortfalls	Recycled within system. Delivering ecosystem services & buffering against shortfalls	Recovered losses sustain accustomed flows e.g. watertables/ new streams	Generally not well understood
Views on savings of losses	Responding to sub-field water shortages (drought or design)	Improves irrigation scheduling, reduces other inputs (energy)	Allows crop expansion and/or conserving dam water	Savings connected to water allocation (normatively and problematically)	
Science and social science on views	What does the plant need? What in-field water control is best?	What acceptable/ traceable losses to the group of farmers?	What acceptable/ traceable losses to the the whole system?	How to define the boundaries of WA fractions?	Why do high-level water officers hold such firm views on losses?

Dimension G: Water redistribution and allocation via IE

Factors	1 Sub-field	2 Field, farm, tertiary irrigation unit	3 Irrigation system	4 Basin, aquifer, multiple irrigation systems	5 Global, national, sectors, firms
Water redistribution and allocation questions	"How can I distribute available water around my crops and improve scheduling timing?" "How do I make do with less water?"	"How do I expand production from savings or bank water in storage?"	"How to expand production and/or, improve timing and distribution between farms?" "How to adjust to caps on withdrawals and consumption?"	"How to reallocate water to other sectors out of irrigation?" "What is role of efficiency in reducing/ increasing total water consumption?"	"What economic goals for this basin/nation and how enabled by water allocation?"
Likely destinations of 'savings & losses'	To proprietor; forestalled losses over time; to crops within field/farm	Fates of losses 'saved' commonly go to the proprietor giving positive or negative impacts on downstream and immediate neighbours		Recovered losses commonly 'saved' to irrigation expansion (proprietor)	Savings intended for society and/or nature (but rarely achieved in reality)
Influences on water redistribution and allocation	Cropping patterns, soil distribution, farming and market choices, changes to infrastructure. Incremental vs step change technological adoption by farmers		Headworks and licences for abstraction. Intra-system design for water distribution. Indirect land use changes	Pricing & reform of water abstraction licences. Design of irrigation infrastructure. Measures to cap withdrawals	Water law in basin/country. National economic priorities. Global crop & land prices. Links to water accounting
Losses / savings as a 'commons'	Water allocation via losses & savings asks how to treat reduced ('freed up') losses as a commons (paracommons). E.g. how should stakeholders conceptually and physically 'meet' in a commons forum when ordinarily they are not commoners of this potential resource, especially if existing water law mediates the fates of irrigation losses				

Fig. 4. Dimensions F (Views on efficiency losses, wastes, savings) and G (Water redistribution/allocation via IE).

and livelihoods, and; 7) political, legal, institutional, economic and financial. For example, with regards to the fifth factor (meteorological, hydrological and environmental), scale is important. At the sub-field and field scales (1 and 2) micro-climates, either natural or induced by shade cloth and greenhouses, affect crop transpiration and irrigation demand and uniformity (Ahemd et al., 2016). Similarly, the river basin and global scales (4 and 5) experience climate and weather at these larger regional scales. At larger scale irrigation also has effects on climate, see e.g. De Vrese et al. (2016).

These dynamic contextual factors corroborate observations in science dimension E that IE is not sitting in a laboratory comprising predictable inputs, investments, behaviours and outcomes. Rather, a complex and stochastic environment, also subject to climate change and non-stationarity (Gober, 2018) means that each irrigator, irrigation system and river basin has unique properties that change over time, sometimes rapidly so. This in turn means these systems need to be 'read' individually and frequently for how IE and component parts change (Malek et al., 2018), are monitored (Pousa et al., 2019) and interrogated (Molden et al., 2001). A second point is that over time several factors change the hydrology of catchments making it practically and accurately difficult to ascribe hydrological change to irrigation efficiency effects on water consumption alone (also see Wheeler et al. (2020) regarding infrastructural and institutional changes that affect water extractions). Other examples include changing intra- and inter-annual rainfall distribution and evapotranspiration (Petrone et al., 2010) increasingly affected by and related to climate change (Dey and Mishra, 2017); changes to rainfall-runoff relationships caused by the invasion of alien species (Le Maitre et al., 2015); de/afforestation (Nadal-Romero et al., 2016); rainfed crop expansion plus the distribution of annuals versus perennials (Zhang et al., 2012); urbanisation (Braud et al., 2013), and; consolidation of farms and water licences resulting in greater withdrawals from previously little-used licences (Woodhouse, 2012). Furthermore, these dynamics allow irrigation actors to be opportunistic e.g. to increase groundwater use during drought events (Ward, 2014).

Dimension J: IE research-policy procurement and leadership. This discursive dimension explores whether and how IE research in dimension 'E' (science approaches) sufficiently guides policy in dimension A (to address water development challenges). Dimension J asks four main questions; 1) who is (not) pushing for and procuring IE research innovation (Chicot and Matt, 2018; Wesseling and Edquist, 2018) and therefore what is the directionality of dialogue between research, practice and policy (Edler and Boon, 2018); 2) how practice, research and policy combine to (de)legitimise and co-produce the framing of key questions in irrigation efficiency (Arnott et al., 2020); 3) how research questions are specifically aligned to various water challenges, and; 4) what factors structure the ability of researchers, farmers, policy-makers, politicians and other stakeholders to open up, work on and take up advice from different scales, sources, and stakeholders. In other words, dimension J is concerned with how researchers follow fashions or stay within silos (Wichelns, 2017) or how a lack of systematic monitoring (Lopez-Gunn et al., 2012) sanction research and policy questions while hiding others.

To exemplify; without a more transformative probing of IE, research and policy are at risk of drifting into a situation where a new 'scale 4' orthodoxy entrenches; that higher IE enabled by a step-change from gravity/canal to drip irrigation increases water consumption and this, if it is not capped, reduces an ability to allocate water out of irrigation (Grafton et al., 2018). Three alternatives suggest more research is required: First, whether this scale 4 orthodoxy undermines support to scale 1–3 farmers on shared canal systems growing broadacre field crops (e.g. rice) not seeking to switch to drip. Second, whether scale 1–3 'savings' of water might under some circumstances deliver scale 4 savings without the need for capping consumption, as might happen if land area for expansion is limited. Third, whether in trying to effect scale 4 allocable savings, it is better to work 'bottom up' in scales 1–3 rather than by capping withdrawals at scale 4 and cascading these caps to the lower scales. These alternatives cannot be answered using cost-efficient or desk-based research methods (e.g. questionnaires emailed to stakeholders, modelling and the analysis of satellite data). Instead they need to be 'procured' as ambitious research projects designed to meet major water challenges (Wesseling and Edquist, 2018). Other examples of research-policy procurement include:

- Identifying social and economic research to unpick the motivations, drivers and challenges of farmers responding to pressures to adopt new IE technology.
- Inquiring how IE pluralism, welcoming different modes, motives and methods, allows canal/gravity irrigators to effectively co-manage irrigation systems more efficiently and equitably while contributing to water stewardship standards and river basin objectives (Boelens and Vos, 2014).
- Determining what agenda, including the reform of water laws, could transform the research of river basin governance by viewing the allocation of savings as a 'commons' type problem (Lankford, 2013).
- Uncovering how alliances and incentives found amongst scale 5 actors such as financing organisations (e.g. IFC), global consulting companies (for example McKinsey and WRG2030) and governments, shape high-level narratives (Hepworth and Orr, 2013; Newborne and Dalton, 2016) to the detriment of more affordable, incremental, hybrid, farmer-originated and widely discussed solutions.

4. Discussion - interpretations of the irrigation efficiency matrix

To explore the utility of the IEM we now; discuss the objectives of our framework approach to IE; unpack IE's pitfalls and paradoxes in more detail; provide further thinking on IE science and research. and; discuss its limitations and applications in practical and policy work.

4.1. The objectives of a framework approach to IE

This paper sets out to frame irrigation efficiency as a dialogue that welcomes a wide range of perspectives and scales. It does this by articulating IE as a multi-modal boundary object via a 5-scale × 10-dimension matrix. Accordingly, the IEM framework invites diverse actors to examine irrigation efficiency through its contrasting perspectives, promises, pitfalls and paradoxes. For example with regards to irrigation 'wastes and losses', normative IE policy commonly found in scale 5 in dimension D ("irrigation efficiency must be improved to reduce waste") can be situated alongside farmer-centred mediation for understanding dimension F in scales 1 and 2 ("my neighbours waste water") and a need to understand IE via a paradox-understanding critical lens ("a waste is not a waste if it returns to the basin") for understanding water allocation in scale 4. The IEM framework asks not that one perspective should outcompete another, but that they are understood as legitimate concerns and, within specific systems and situations, are harnessed in order to manage water more carefully and appropriately.

A second objective of a framework approach to IE is that it welcomes different scientific and lay understandings regarding the measures and associated/proxy measures of IE (see also Appendix B). We argue that the many practical and observable criteria to assess water control in irrigation systems (e.g. timing, area covered, crop profiles, adequacy and uniformity of water supply networks) are more fully recognised and assessed in the lower scales 1–3 in order to reveal systemic knowledge about IE and WP. However, these measures, proxies and connections do not need to be so well understood by higher-level actors less familiar with the intricacies of water control. Thus, actors in scales 4 and 5 might justifiably refer to the relatively poorly defined term 'irrigation efficiency' when discussing water control and performance.

A third objective cautions that IE in the lower scales is influenced by its political economy. The IEM shows that discussions in scale 5 around food (production and security), water management and investment are

Dimension H: Views on IE improvement via technology

Five scales → / ↓ Factors	1 Sub-field	2 Field, farm, tertiary irrigation unit	3 Irrigation system	4 Basin, aquifer, multiple irrigation systems	5 Global, national, sectors, firms
Origins of change in technologies	1) Stand-alone, piecemeal adoption; 2) part of irrigation rehabilitation; 3) supply-side thinking; 4) responding to farmer requests or farmer-to-farmer dissemination; 5) rarely tied to new licences and caps on withdrawals				
Entry questions or statements on 'modern technology'	(Single farmer): I am (not) persuaded that external 'expert' hi-tech solutions work for me	Farmer group inertia or appetite to adopt new improvements (cost, selling, conditions, experience)	Inertia or appetite for (fashionable) technologies to improve IE (cost, selling, conditions, experience)	Category thinking on technology and how they offer higher IE: drip > sprinkler > gravity. Category thinking: modern > 'traditional'	
Technological orthodoxies	Precision irrigation water to root zone e.g. drip	Technology promises to improve efficiency	Tech interventions: drip, canal lining, laser-levelling	Policies and incentives towards formal 'modern irrigation' and performance improvement	
Costs of tech orthodoxies	With drip; increased energy costs, plastics waste; dripper breakages	IE not seen as socio-technical. Farmers' ideas not listened to	Modernisation to 'save water'. Fixing symptoms not underlying causes of IE	IE improvements can increase water consumption	IE modernisation costly and economically inefficient
Yet other technology views	Informal ways to manage soil-water e.g. plot size, plant density, soil ridging	Farmers & artisans 'fix' visible water loss problems over time	Many landscape & farming niches giving other options; e.g. increase modularity	How to support multiple irrigation systems on different pathways	Daily practice of managing water generally not well understood at this scale
Non-IE technology	Uptake of GPS, drones, robots, fin-tech, mobile apps, internet connectivity			R&D on non-IE technology; fit with financial technology	

Dimension I: The wider dynamic context of IE

Factors	1 Sub-field	2 Field, farm, tertiary irrigation unit	3 Irrigation system	4 Basin, aquifer, multiple irrigation systems	5 Global, national, sectors, firms
Crops, crop and market systems	Crops compete with each other. Diseases, ageing	Crop choices responding to markets. Farmer experience	Row or field crops 'fit' their irrigation system. System inertia	Local, national and global markets for crops. Volume and quality demand. Export and prices. Consumer preferences	
Irrigation systems	IE sits within the behaviours and dynamics of irrigation systems co-created by long and short-term decisions in infrastructure, technology, management and operation			Investment decisions in irrigation sector and systems	
Farming systems	Automation. Ageing farmer population	Input and equipment prices. Services and extension	Land and farm consolidation. Labour laws	Urbanisation effects on land conversion	Private equity driving farm commercialisation
Water access/supply infrastructure & costs	Local small on-farm dams and shallow boreholes. Changing costs of energy to lift and distribute water, e.g. solar energy		Increasing number of boreholes and medium and large dams leading to greater capture of runoff and likely irrigation withdrawals & consumption of water. Political favour or disapproval for large dams		
Meteorological, hydrological, environmental Catchment	Spatial and temporal variability of surface and groundwater accentuated by drought, flood, rainfall events and patterns, also further driven by climate change. Changes in soil fertility and salts. Night-day temperatures changes affecting ripening. Ecosystem services. Changing water qualities in/from groundwater. Micro-climate effects in fields and sub-fields			Basin/aquifer supply declining & variable. Changing rainfall-runoff relationship due to changing rainfall patterns, urbanisation, agriculture, forest cover, invasive plants and artificial storage	
Human, education, livelihoods	'Normal' farmer needs (e.g. day time irrigation), education and mistakes shape daily management of water		'Normal' engineer and WUA behaviours. Education	Powerful actors with little experience of water & farming increasingly shape land and water debates	
Political, legal, institutional, economic, financial	Farmers face pressures from local and national political interests; influence of historical & reformed licences; they face shifting priorities on incentives, subsidies and grants		Changes to ownership of total & sub-systems and to prices & costs of drivers of IE change	Legal framework for licences. Political & investor interests. Fiscal constraints	Politicians & investors face fiscal, customer & voter pressures. Global finance

Dimension J: IE research-policy procurement and leadership

Directionality, framing, biases, financing, gaps and recursive connections driving IE research and policy innovation & funding

Fig. 5. Dimensions H (IE technologies), I (Wider dynamic context) and J (Research-policy procurement).

often (if not always) disconnected from the realities in scales 1–4 and the experiences of the past. The future of our food, water and irrigation systems is no longer solely driven by farmers making choices about their land and water, but by a set and scale of actors who all have some interest and varying influence in irrigation. Scale 5 actors have strongly held opinions on the matter of IE - and these often poorly checked opinions are driving large investments and dominating narratives and decision-making. The purpose of the IEM is therefore to make clear that with respect to IE knowledges, powerful scale 5 forces are worryingly disconnected from scales 1–4.

4.2. Types of pitfalls and paradoxes

Drawing on the within-, multi- and cross-scale ideas of Scholes et al. (2013), we interpret four types of pitfalls and three types of paradoxes arising within the IEM (Fig. 6). We advise that this introductory list is not exhaustive, plus within each type are many sub-types, and we foresee that the definitions of and distinction between pitfalls and the more contradictory or more material paradoxes will need further work. Four pitfalls are briefly described:

1. Multi-scale pitfalls (P1): This arises when research and other interventions, which ideally should consider multiple or all scales, are directed at one scale or at no particular scale. For example, scale 5 funders fail to commission an 'all scales 1-5' approach to researching IE.
2. Cross-scale pitfalls (P2): This type of pitfall occurs when changes in IE management in one scale specifically fails to reference how these affect IE and water in another scale. In the example given in Fig. 6, P2 is shown as revised scale 4 river basin allocation quotas that do not fully recognise how local scale 1–2 actors might bear these.
3. Cross-dimension pitfalls (P3): This kind of pitfall emphases risks that arise across dimensions when focussing only on one scale or moving from one scale to another. In particular, the ten IE motives in dimension D change across the scales bringing possible misunderstanding. Thus farmers in scales 2 and 3 might be managing local disagreements about payment contributions to maintenance and operation (motives 2 and 7) while being buffeted by political motives (no. 8) levered by scale 5 politicians seeking to enrol constituents via subsidies or by scale 5 corporate actors making investments in their supply chains (Hepworth and Orr, 2013; Marston et al., 2018). In another example, exclusive reference to a prevailing view on the 'science of IE' in dimension E such as the need to calculate a dimensionless IE ratio undermines how proxy IE information might support a range of dimension D motives across different scales. (To illustrate the latter; IE guides or motivates design improvements to an irrigation unit for which a simple metric, such as the ratio of area irrigated per volume supplied from one year to another, can be usefully provided).
4. Within-scale/within-dimension pitfalls (P4): This arises 'within an IEM cell/mode' when, in an intersection of scale and dimension, different or unexpected objectives and outcomes occur over time or laterally from one locality to another. Here, observers run the risk of misinterpreting the fluid and unique IE motives of individuals in each scale. For example, the crop protection motives of farmers to 'save water' in order to eke out a limited supply during a drought (see Appendix C) may be different to motives to 'save water' in more humid periods resulting in other hydrological, agronomic and operational outcomes. Moreover, these flexible farmer-motive pitfalls are not grasped when scientists, drawing on other motives and scales, assume that 'saving water' relates to river basin water allocation. In a second example; subject to initial conditions and IE interventions, 'losses' can switch from one pathway to another resulting in different hydrological outcomes. Thus, reduced seepage losses, rather than resulting in increased transpiration, might pass to non-beneficial evaporation.

Fig. 6 shows the positions of three types of paradoxes. These are:

1. Cross-scale paradoxes (X1): An action in one scale results in a contrary outcome in another scale. For example, attempts to increase efficiency and 'save' water at the field level (scales 1–2) increases total water consumption in the scale 4 river basin.
2. Cross-dimension paradoxes (X2): Within one IEM scale a paradox might arise between two or more dimensions. For example, changes to IE technology in dimension H can increase energy consumption (dimension D) as Daccache et al. (2014) showed when examining the modernisation of Mediterranean irrigation.
3. Within-scale/within-dimension (mode) paradoxes (X3): For example taking science dimension E, an irrigation system can have different efficiencies depending on how IE is calculated – e.g. via a classical or effective efficiency calculation. In other example, looking at motives in dimension D, a higher IE aiming to produce more food might negatively affect the resilience of the catchment and its ecological functioning in the face of droughts (Scott et al., 2014).

4.3. Towards a wider irrigation efficiency methodology and theory

The IEM informs the comprehension of irrigation efficiency within an irrigated river basin. It reveals why a theory of IE depends on how we construct a multi-modal understanding of nested systems using five scales. On one hand, if a river basin is seen as a single monolithic 'scale 4 block', then the Law of Conservation of Mass, annual time periods and basin-scale 'inputs' and 'outputs' help construct that model (Grafton et al., 2018). By contrast, if the irrigation hydrology of a river basin is defined by many heterogeneous scale 1–3 behaviours and components (such as weather, channels, land height, soil quality, individual fields, farms and farmers) affecting many small dividing and cascading water flows 'lost to the locality and local time frame' set against water control objectives with timing needs, then the relative but summarised irrigation performance of these smaller units over short time periods is the more appropriate frame (Lankford, 2006). We are not arguing in favour of one default over another, but rather that a judgement must be made regarding a balance or hybrid of approaches dependent on the policy aims and effectiveness being sought (Cai et al., 2001).

A new 'methodology' approach to IE research will depend on an appetite to move from single methods to multiple, mixed methods that provide relevant information to understand the heterogenous and often empirical data-short evolving stories of irrigation systems and river basins. Furthermore, while we need within- and multi-scale disciplines (Hess and Knox, 2013) such as sociologists, economists, engineers, agronomists, this needs to respect the aims, language and terms used by people representing other scales who don't see IE in strong disciplinary terms – people such as farmers, business investors and policy-makers (Domínguez Guzmán et al., 2017). Other insights also follow; research is needed that supports and monitors farmers experimenting with irrigation technologies rather than promoting new technologies assumed to be desirable that farmers, operating with partial knowledge of the total system (Levidow et al., 2014), seem so ready to adopt. Furthermore, as tensions over water for agriculture, development and the environment become increasingly acute, it is necessary to reflect on how IE thinking is being shaped by the limited funding of IE research in turn limiting the number of voices heard (re dimension J).

4.4. Who is the IEM for?

The IEM is for two major groups of actors and sectors; first those involved in research, academic debate, and theory-building such as scholars, scientists, action-researchers, students and academics. Second it is for those involved in promoting or responding to a particular practicable action or policy on irrigation efficiency, such as farmers, irrigation managers, engineers, water lawyers, basin officers and consultants based in organisations diverse as extension services, river basin

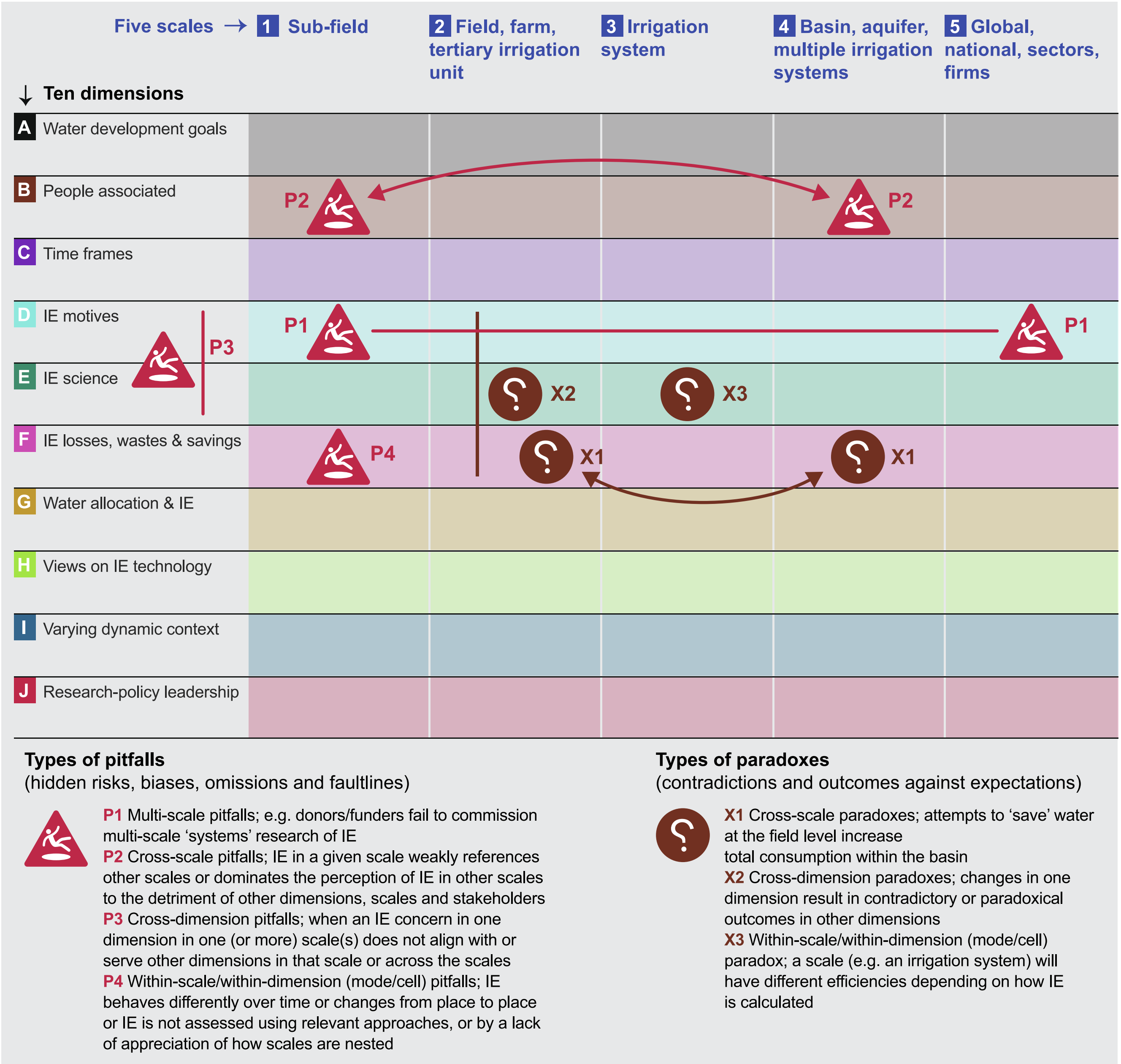

Fig. 6. Types of pitfalls and paradoxes arising within the irrigation efficiency matrix.

and government offices, think-tanks, consulting companies, NGOs and charities, irrigation firms, development finance banks and bilateral donors.

4.5. IEM applied to water and irrigation policy

Functioning as a guide to irrigation efficiency perspectives and consequences, the IEM does not advise IE policy in a narrow and instrumental way. The IEM does not operate normatively to argue that irrigation systems should as a blanket recommendation 'become more efficient' or that 'this kind of technology is required'. Instead, the IEM is one of many inputs to irrigation and water policy formulation. Accordingly, we draw up four related policy notes:-

A dialogue tool. On top of being seen as a measure, technology or goal, irrigation efficiency is a discussion. In this way, the IEM acts as an aid for multi-stakeholder platforms to arrive at a common understanding on IE recognising that powerful lobbies and actors are situated within scales and dimensions. For example, with reference to 'climate-smart irrigation', the IEM implies smart debate rather than smart technology is required.

Cross-scale thinking. Policy for irrigation should seek cross-scale checks on the consequences of changes to irrigation efficiency at different scales. A policy of devolving water management responsibilities to farmers and lower levels of irrigation systems should be set against their cumulative effects on patterns of water consumption at the catchment level (Grafton et al., 2018).

Greater granularity. The IEM views irrigation systems and efficiency are unique and individual in time and place. Therefore policy makers should refrain from making blanket recommendations and instead promote programmes that allow for specific support contingent on irrigation features and trajectories (Shah et al., 2012). An example of this more granular case-specific approach can be seen in how the IEM might assist with analytical work on SDG indicator 6.4.1 on efficiency. While work has been done on water stress indicators (Vanham et al., 2018) or by defining water use efficiency as water productivity in for example US dollars value per cubic metre withdrawn (Giupponi et al., 2018), less progress has been made on indicators of irrigation efficiency within irrigated agriculture. One way forward is to provide an IEM-type SDG framework to guide individual irrigation systems on setting their own measures of irrigation performance and, no matter how informal and vernacular, to establish these as the basis on which they report gradual improvements. Thus the IEM supports Nastiti's (2015) call for local monitoring within a country-wide or global framing, and echoes IWMI's principles of analysing SDG metrics at multiple scales (van der Bliek et al., 2014) and via multiple frameworks (Sadoff et al., 2020).

Questioning IE scientists and science. Decision-makers receiving IE policy advice from water and irrigation scientists should probe the consensus, theories and data behind the advice. For example, the view that raising irrigation efficiency leads to a Jevons rebound in water consumption (Wheeler et al., 2020), while an important concern, should be questioned if it comes to dominate IE policy. The Jevons rebound caution 'sees' IE from the perspective of scales 3 and 4 (the irrigation system and basin) rather via the benefits of raising IE in scales 1–2 (especially in responding to drought). Furthermore, originally, Jevons' observed that higher demand for goods and raw materials (e.g. coal) was caused by lower prices brought by higher processing efficiency (Alcott et al., 2012). In irrigation efficiency we are not witnessing a price-mediated rebound but are concerned with fates of material flows of water in different and complex nested scales. So unless it is certain that with increases in irrigation efficiency, all irrigation losses have switched from previously 'recycled to the catchment' to being consumed by transpiration (the scenario in which the Jevons paradox applies) we should be far more interested in the specific and unique types and fates of flows associated with changing irrigation efficiency at different times and scales. For example, in gravity and sprinkler irrigated sugarcane, the first three months of the season sees approximately a quarter of field evapotranspiration accounted for by evaporation from bare soil between young cane as a non-recovered water 'loss'. Even if efficiency in this part of the season could be improved, there would be no or little additional consumption of water leading to a rebound.

4.6. What are the practical applications and limitations of the IEM?

In its current guise the IEM is not a practical tool in a conventional sense; it does not inform irrigation stakeholders what to practise or to implement. Rather, it operates as a sounding board to question the validity of IE practices dominated by single-scale, -technology and -disciplinary assumptions and biases. The matrix helps to query what is thought to be correct for one scale and geography applies more generally, and it shows how multiple paradoxes arise within IE (and not just the Jevon's paradox).

The matrix has immediate practical benefits in addressing the disciplines and knowledges of those involved in irrigation. For example, the IEM practically informs irrigation training, teaching and design. Many students are taught to use IE as a design or performance variable in scales 1–3. It is rarely made explicit to students that in the messy world of corporate, catchment and national policy in scales 4 and 5, IE might be used discursively or applied differently. Furthermore, students and engineers need to be made aware that long-standing norms and protocols to 'design correctly' or be efficient with water applicable in scales 1–3 might have unintended consequences in those same scales and at the national and catchment scales (van der Kooij et al., 2017). Similarly, the matrix serves those without an irrigation engineering background who might think that improving IE has only positive outcomes. The IEM also asks that they do not unquestioningly take the opposite view; that raising irrigation efficiency invariably increases water consumption.

Future work could develop the IEM to create practical tools – in brief form we outline some of these in Box 1. For example, used by irrigation investors, the IEM will have practical benefits when drawing up plans, budgets and expenditures on programmes to raise the performance of irrigation systems. A matrix that invites deeper questioning on IE will allow funders and related stakeholders to more thoroughly question the costs, optimism and modalities for implementation and monitoring. Ideally, it should also prevent the lack of accountability (and unintended consequences) seen with national or river basin programmes to upgrade irrigation and manage scarce resources (Lopez-Gunn et al., 2012; Wheeler et al., 2020)

Box 1
Future applications of the IEM.

- Drawing up clearer guidance on donor approaches to IE planning, programming and budgeting, informed by analysing the track record of interventions and their costs and consequences
- Creation of regulatory instruments for different actors that are shaping current investments in this space such as manufacturers of irrigation equipment, financial services providers and irrigation service providers.
- Preparation of publications on technical and social IE engagement that follow the MASSCOTE approach to engaging with irrigation performance (Renault et al., 2007).
- Classifying types of irrigation efficiency and likely behaviours for water flows and other factors in irrigation systems and their catchment using multi-criteria (Molden et al., 2001; Sawicz et al., 2014).
- Adding to current water accounting methods by drawing on proxy, vernacular and local measures and understandings of IE (FAO, 2018; Lankford, 2006) (See also the discussion on the SDG water target in Section 4.5 above).
- Creating simple models (see Appendix C), infographics and videos that capture IE's multi-faceted nature.

With regards to limitations, we accept that the topic is complicated and that the framework requires a deeper engagement with IE than perhaps most actors and stakeholders normally give to the topic. In addition, despite the IEM's aim to bridge the current polarisation in debates around irrigation efficiency, we foresee that there will be parties who will not accept a multi-scale, multi-dimensional framing of IE. For example, some actors may continue to define irrigation efficiency via its original dimensionless ratio and never accept that IE expresses itself to different actors and settings via proxy (e.g. timing), vernacular or relative measures. Or others might accept the broad principles of the IEM, but argue that parts of the matrix (e.g. a scale 4 Jevons rebound) should govern IE debate. For these reasons, we see IE and the IEM best 'animated' via meetings and discussion, preferably held on irrigation systems, leading either to immediate problem-solving or to long-term empirical research.

Furthermore, the highly dynamic environment that the IEM attempts to reflect and illustrate is, to a certain extent, statically depicted as a result of its textual/tabular representation. However, as this is groundwork for conceptually framing the multi-scalar environment of IE, future development could generate computational, graphical, informational and intervention models that more dynamically represent the ever-changing IEM dimensions and their interactions across scales. Appendix C is a brief introduction to some worked quantitative examples so show how the matrix can be employed.

We accept that there will be circumstances where IEM will not be utilised by stakeholders to participate in conversations about irrigation efficiency. For example, although the matrix contributes to discussions on society's relationship with the (over)consumption of resources (Princen, 2003), it does not intrinsically articulate a normative or philosophical response to this question. Furthermore, it can be useful for parties not to discuss different interpretations on IE especially where political or financial gain and an imagined future livelihood gain are intertwined ('let's increase IE, we'll all benefit'). Opening up what is exactly meant by IE, where saved water goes, and which minority sectors (shallow groundwater users, ecological niches, etc) are affected might be very unpalatable to politicians and ministry bureaucrats who gain from conventional patronage-type and blue-print approaches to irrigation investments and management (Molle et al., 2009; Vermillion, 2005).

Related to these points, despite attempts at inclusivity and depth, the IEM does not sufficiently include all relevant details on stakeholders, scales and dimensions, or sufficiently emphasise how fluid IE is across dimensions and scales. For example, from an engineer's point of view, the matrix skims over the protocols of irrigation design, and from a social scientist's viewpoint, it skirts around the significance of the political economy of IE. Put simply, there are considerable and critical details in each of the IEM's modes/intersections not captured in the framework or this paper. As such, we are concerned the IEM could be employed superficially as a check-boxing activity to avoid scrutinising IE programmes and projects. Referring to Box 1, future iterations could see the development of sub-modules of the IEM to further unpack these concerns at different scales.

Furthermore, the IEM is unable to recommend governance models for managing IE, irrigated systems and their hydrological consequences. For example, the IEM cannot instruct stakeholders how they might create new ownership and management arrangements for irrigated systems in scales 1–3. This caution also applies to putative reforms of irrigated river basins in scale 4 where state water tenure and regulations meet different types (e.g. private, community, parastatal) of irrigation tenure and management. And with respect to scale 5, and by extension to scales 1–4, the IEM cannot specify frameworks for the global governance of irrigation hydrology to explain both the roles of governments, global finance bodies and think-tanks and the position of corporates and consulting firms in this endeavour (Newborne and Dalton, 2016; Rudebeck, 2019). However, a counterpoint to this lack of specification is that the IEM can contribute to discussions on governance models by examining how they accommodate modal IE thinking.

5. Conclusions

The IEM invites different actors to view both the separations and connections between water challenges, irrigation and irrigation efficiency from different perspectives and to situate their own understanding into a wider IE theory and knowledge framing (Boelens and Vos, 2012). The IEM cautions that IE pitfalls and paradoxes arise because many dimensions of IE intersect with multiple scales in ways that allow for a great number of outcomes which are often poorly understood or governed. In addition, pitfalls and paradoxes are more likely to be maintained when actors and arguments remain 'stuck' in one column (scale), row (dimension) or cell (mode) within the matrix.

By viewing IE as systemically arising within and bridging across the five scales, we argue that actions and outcomes in lower scales (1 and 2) create impacts in scales 4 and 5 and vice versa; policies adopted by powerful players in scales 4 and 5 shape opportunities in the lower scales. Furthermore, indirect effects apply; within scale 2, non-farm actors (e.g. representing domestic water and the environment), and within scale 3 and 4, urban, industrial and other 'competitors' for water, have increasingly vested stakes in IE. Such multi- and cross-scale accountability and representation (or lack of) imply significant justice and equity effects when IE policies are critically examined. The matrix also provides deeper insights into how water losses can be seen as pejorative (e.g. as 'wastes'), neutral, or positive depending on conditions, or under changing IE conditions, as redistributive and therefore who might gain and lose from these changes.

Furthermore, we argue the irrigation efficiency matrix provides a multi-modal framework through which actors can navigate the polarisation that has driven the debate surrounding IE and, in our view, hampered fuller research and monitoring of IE. This polarisation, which we do not expect to eliminate (Dewulf et al., 2007), occurs for various reasons. One arises because of the belief that, on the one hand irrigation losses are mostly recovered within the basin and therefore need not be seen as losses, and on the other hand, that irrigation losses represent a substantial volume of water for reallocation. For an example of these polarised views, see Frederiksen and Allen (2011), Gleick et al. (2011) and Frederiksen et al. (2012). Others contend that losses, even if mostly recovered, are associated with other IE motives, especially in scales 1–3, and thus carry 'transactional costs' in the form of poorer soil and water quality, loss of command and placement, and delayed irrigation timing on canal networks with deleterious effects on crop production.

The matrix positions IE alongside relevant water goals and challenges of sustainable development including boosting crop production, managing water allocation for economic growth, responding to technological and farmer innovation, enhancing resilience, and securing environmental services and goods. As such, the IEM revisits and renews the project of integrating IE into water's multiple scales and dimensions (Keller et al., 1996). Accordingly, we call for transformative research of efficiency and productivity of irrigation systems, particularly canal irrigation, continuing the kind of cross-disciplinary work exemplified by Venot et al. (2017). This 'systems approach' aims to enable a deeper and more respectful understanding and scrutiny of how IE has different meanings and values for people in different locations and scales, enabling actors to ask better questions of irrigation and therefore to make better informed decisions on sustaining water resources for the environment, economy and society.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Terms and definitions

A.1. Key terms and definitions

An irrigated system is defined as an entity situated within or across the five scales that undergoes, experiences or contains irrigation and its outcomes. (By contrast, an irrigation system is an entity found in scale 3 of the IEM, comprising entities in scales 1–2). An irrigated system is therefore a single irrigated plant in a field, part or whole irrigation system, a catchment dominated by irrigation, or a global food chain comprising irrigated products. Such systems have their own identity and behaviour but importantly are seen through the eyes of farmers and other actors, often immersed in and vexed by the challenges of managing water. Irrigated systems are also networked and/or neighbouring entities sitting within one scale.

Modal irrigation efficiency invites multiple modes of understanding irrigation efficiency arising from different dimensions and cross-scale perspectives on the performant management of the hydrology of irrigated systems and their beneficial consumption of water.

The hydrology of irrigated systems can be understood as outlined in the next four paragraphs. Using this four-part definition, irrigation hydrology is connected to environmental fluxes, people, changing technologies of irrigation control and to wider water allocation concerns, and as such, requires the application of accounting, agrometeorological, agronomic, anthropological, engineering, farming, hydrological, hydrogeological, political and social sciences and disciplines, as well as local vernacular knowledges.

1. **Physical irrigation hydrology**, drawing on Wallender and Grismer (2002); the movement, distribution, timing, dividing and combining of rain-, soil-, ground-, surface- and irrigation water, affected by irrigation technology, management, atmospheric and natural factors, flowing into, cascading through, retained within, altered, and exiting irrigated systems comprising temporal and spatially arrayed entities within nested scales from the plant to the catchment and global in order to meet crop transpiration and other beneficial water-use objectives.
2. **Irrigation hydrology fraction accounting**; drawing on Perry (2011): the application of an accounting classification of the inflows and outflows (disposals) of the physical hydrology of irrigated systems. Fraction accounting usually derives post-hoc indicative water accounts of larger scale entities such as irrigation systems and catchments within longer time-steps (i.e. annual); the purpose of which is to cross-check claims for water saving and irrigation efficiency taking into account the hydrology of the next higher scale. (In terms of corporate and company finances, fraction accounts would be known as statutory final accounts or year-end profit and loss accounts.
3. **Irrigation management metrics**; drawing on Lankford (2013), the recurrent, ongoing and small time step (hourly, daily, weekly) collation and analysis of metrics of the performant management and control of irrigation hydrology usually applied to the scale of an irrigation system and below. These metrics examine activities such as the scheduling, timing and distribution of irrigation water within and between irrigation entities allowing the derivation of performance indicators such as equity, adequacy, uniformity and efficiency of irrigation. (In company finances, these are 'management accounts' generated on a regular basis usually monthly by managers to monitor the running of their company).
4. **Irrigation hydrology gains appropriation**; drawing on Lankford (2013) this measures, tracks and traces how material gains, salvages and savings made at different scales are appropriated by or distributed/allocated to different systems, actors and sectors for further use and consumption. (These have their equivalent in financial reporting. Termed 'appropriation accounts of profit and loss', they are used to track how profits are distributed to different parts of an organisation including shareholders).

A.2. IEM matrix definitions

IE matrix (IEM); is a conceptual framework that maps and contains irrigation efficiency as a technically and hydro-socially mediated performance measure and boundary object. It situates ten discursive dimensions of the science, practice, policy and politics of irrigation efficiency within and across five spatial scales that in turn underpin agricultural production, water control, management, consumption and allocation, and that link through to global water and food challenges including the UN's Sustainable Development Goals.

Discursive dimensions; these are the rows in the IEM. Ten dimensions (A to J) solicit discussion on the values, perspectives and motives of those interested in irrigation efficiency, its associated factors, and the intended and unintended consequences of changes in IE.

Scales; these are the five columns in the IEM. Drawing on common deployment within the irrigation and water literature, scales run from the plant level through to the catchment and global levels. In the IEM, scales might include and combine sub-scales.

Modes/cells; these are the cells of the matrix found at intersections between rows and columns. On paper, via its 5 × 10 grid, the IEM comprises 50 modes of using and discussing IE – though in effect many of these conjoin together into fewer modes.

A.3. Other terms and definitions arising within the paper

Boundary object; defined Trompette and Vinck (2009) (pages d-e): "The boundary object is "multiple": abstract and concrete, general and specific, conventional and user-adapted, material and conceptual (a database, a protocol). It is a partial and temporary bridge which is fairly unstructured when used jointly and highly structured when used within one of the worlds involved. It has different meanings in the different worlds, but those meanings are sufficiently structured to be recognised by the other. The notion is used to describe how actors maintain their differences and their cooperation, how they manage and restrict variety, how they coordinate in space and time. It qualifies the way in which actors establish and maintain coherence between interacting social worlds, without making them uniform or transparent from one to the other. Actors in these social worlds can, thanks to the boundary object, negotiate their differences and establish agreement on their respective points of view".

Hydrosocial territories; quoting from the abstract of Boelens et al. (2016) (page 1) these are as "spatial configurations of people, institutions, water flows, hydraulic technology and the biophysical environment that revolve around the control of water".

Losses; Losses should be defined using case-specific analysis which recognises scales and dimensions. For example using scales 3–4 'water accounting fractions' to determine hydrological changes following shifts in IE, losses might be understood as non-recovered/able flows and non-beneficial consumption. However, in scales 1–3, losses are or should be taken as a vernacular, locally determined term to describe water that flows into an irrigation system, or part thereof, but is not transpired in beneficial productive crop growth. Therefore, because losses via the latter perspective are usually 'lost' to the farmers on a local canal network, they can include 'basin recoverable flows'.

Nested system; the IEM views that each lower scale sits (nests) within the scale above it and likewise a higher scale (e.g. the catchment in scale 4) holds a lower scale (e.g. irrigation system in scale 3).

Networked system; in a given scale, crops, fields, farms and farmers are connected together via a network of canals or pipes and water sharing/distribution using that network. This network establishes bifurcating features of irrigation systems not described in simpler 'block' models of irrigation efficiency. Furthermore, when networking is repeated up and down the nested scales, we can see each scale as a fractal or repetition of another scale.

Paracommons; drawing on Lankford (2013) is a commons of, and competition over, the material gains salvaged/freed up by efficiency gains. A paracommons arises because of the supposed fall in consumption in a potential future of a rarely measured but imagined efficient system in comparison to an unmeasured less efficient system of today. The paracommons views that four parties or destinations receive these salvages/gains; the proprietor making the efficiency gain; their immediate neighbour; wider society and the natural environment.

Savings; usually an undefined loosely used word that, like IE, is also a boundary concept, being employed by different actors at different scales for different purposes. It is therefore difficult to provide a single definition. Thus, farmers in scales 1–2 facing a cut in water supply during a drought might 'save' water in order to spread it around their farms as evenly as possible (see Appendix C). Here 'savings' cover all fractions within their withdrawals, not just savings of losses, to describe their attempts to match a new but limited supply to their already established crop water demand. Basin actors in scale 4 are much more interested in how savings in lower scales can 'free up' water for allocation at river basin or regional scales, or perhaps how IE improvements result in contradictory increases in water consumption.

Vernacular; local idioms and terms used by farmers and their service-providers and advisers to describe their understanding of irrigation efficiency and associated management and technology. High level policy-makers not familiar with the technicalities of irrigation systems might also use vernacular or poorly defined IE language with the risk that such terms are interpreted or enrolled as statements of policy with far-reaching consequences.

Appendix B. Science approaches to irrigation efficiency

This Appendix further discusses science approaches to understanding irrigation efficiency (IE). It therefore expands dimension E on science and supports Fig. 3 in the paper.

Fig. B1 places a number of icons and acronyms to represent five types of science approaches to IE across the five vertical scales of the IEM. The science approaches are shown in the five horizontal panels, comprising; new definitions, current IE definition, calculation methods, data methods and associated concepts and studies. The horizontal red lines indicate how a given approach stretches across more than one scale. Brief details and examples of these five panels are given below.

The first row or panel places this paper into the diagram by suggesting that modal irrigation efficiency and a four-part explanation of irrigation hydrology (Appendix A) bridges across all five scales and encompasses various definitions and methods found in the subsequent rows/panels in the diagram.

The second row contains three main theories regarding a defining computation of IE. This means how an equation for calculating IE is 'composed' for different purposes from different types of IE hydrological information. Thus, at the irrigation system level (scales 2 and 3), 'classical irrigation efficiency' (IEc) is the ratio of beneficial evapotranspiration (ETb) to the supply of water to, or withdrawn by, the field or system (Seckler, 1996). Whereas, more useful for basin management (scale 4), 'effective irrigation efficiency' (IEe), is the ratio = ETb/water depleted by irrigation system (Jensen, 2007; Seckler, 1996). Useful for scales 1–3, 'relative irrigation efficiency' compares neighbouring irrigation units and systems, when most factors such as cropping, weather and soils are similar (Lankford, 2006).

The third panel of Fig. B1 considers the different calculation methods for studying irrigation hydrology. While this appears to repeat the second row on theoretical computations, these are the methods by which irrigation hydrology is investigated in order to provide the information for the first row's computations. In simple terms, the third row supports the two upper rows. For example, by using 'irrigation efficiency fractals' (IEF) (Lankford, 2012a) classical IE is 'calculated' by multiplying the efficiencies of different levels (conveyance, distribution and field) of an irrigation system together (Jensen, 1980). This is a different method to that which uses water accounting 'fractions' (Perry, 2011) to arrive at classical IE, or to a method that uses timing calculations. Regarding the latter; the IE, depth of irrigation applied in millimetres (mm), timing of completion (hours), irrigation flow in litres per second (l/s), and area supplied in hectares (ha) fit together with this equation IEc = (mm ×

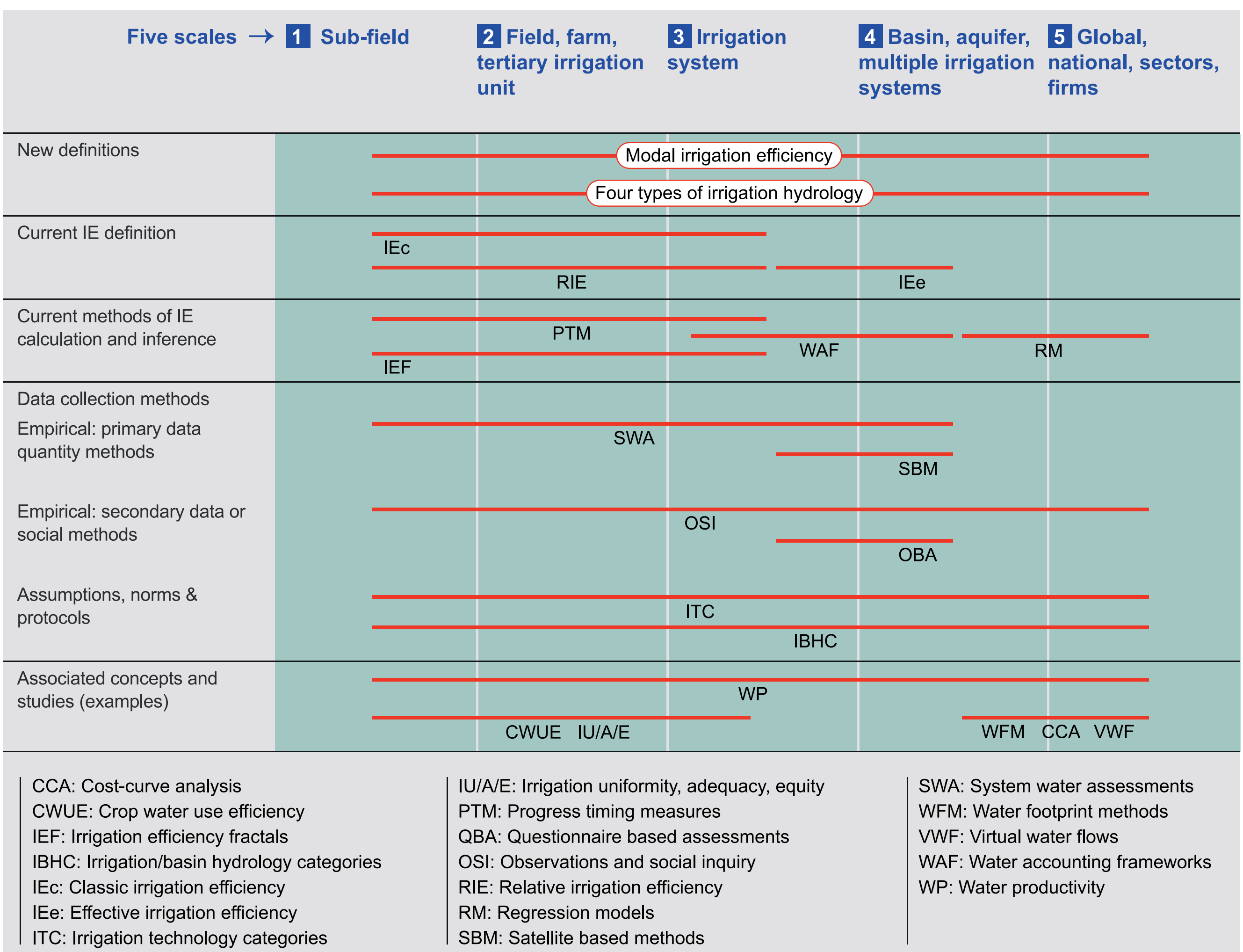

Fig. B1. Expanding Dimension E: exploring science approaches to IE.

ha)/(l/s × h × 0.36), (Lankford, 2006, 2012a). In the latter, by controlling for other variables, an actual performance of irrigation progress can be compared to an idealised target to derive IE (Lankford, 1998).

The larger middle panel presents data collection methods (which feed into the top three panels). In this panel, the icons are also placed vertically to guide readers on whether the measure or method attempts to directly measure IE (at the top of the figure) or is more indirect and qualitative in its approach to IE (towards the middle of the row) or whether the method uses long-held assumptions (bottom of this panel). To exemplify; at the top of the middle panel, system water balances (SWB) by definition entail field and primary measurements of agro-meteorology, agronomy and hydrology to allow a quantification of water balances of a given system. In the middle of the panel, questionnaire based assessments (QBA) collect secondary information on systems, e.g. (Bos and Nugteren, 1990; FAO, 2017).

The bottom panel includes other concepts and studies that are associated with, draw upon, and/or make assumptions about IE. Although there are many concerns driving an interest in irrigation efficiency (e.g. water allocation, water pricing and valuing, the circular economy, and the water-energy-food nexus), Fig. B1 shows three; water productivity, virtual water and water footprints. While these studies bring additional focus on the topic of IE, they should also be interrogated for their motives, claims and assumptions regarding IE and its hydrology and management (Wichelns, 2015).

Fig. B1 allows the following observations and provisos to be made:-

- This Appendix supports the IEM by demonstrating three related points; a) that IE, IE science and irrigation hydrology in combination act as a boundary object recognising (or indeed failing to recognise) that different scales, entry points, actors and disciplines apply different ways of approaching IE; b) that no single measure or method accurately and easily reports on the IE ratio and hydrology, and; c) a judicious combination of different methods creates fuller methodologies required to better understand IE.
- Fig. B1 is not comprehensive. For example, what is not shown are aggregating methods that take data from lower scales to reveal a summary index for a higher scale.
- The red lines depicting the reach of the method/measure across the five scales are indicative only. For example, satellite-based calculations of irrigation hydrology are generally intended to inform the basin and system scale management, though they can record field-level images.
- Fig. B1 has some design limitations. For example, it is difficult to define and place many science approaches using five scales as columns and five broad panels of new and current definitions, calculation, data methods and associated studies.
- Although B1 segregates a particular measure or method, this is often; a) aggregating data from different sources; b) making assumptions and c) working with data from other methods.
- Fig. B1 does not distinguish differences in methods for intensive research irrigation performance and those employed in regular management monitoring.
- There should be no value judgement on the validity or relevancy of different approaches to IE and irrigation hydrology without knowledge of the approach and its objectives and claims. For example, a questionnaire to assess IE might be exploratory because it asks few questions or the questionnaire can more structured, detailed and be accompanied by detailed guidance on how to score and answer questions. However, audiences should be wary of the outputs of exploratory questionnaires being used to inform policy.
- Fig. B1 omits the arrangement of different approaches to IE science into coherent methodologies. For example; an empirical study of IE for a given irrigation system might draw on many of the approaches simultaneously including water balance studies, social inquiry, satellite data and irrigation timing measurements.

Appendix C. Applying the IEM to a hypothetical irrigation system

To practically demonstrate uses of the IEM, we briefly show here how irrigation efficiency and hydrology play out in different ways for a hypothetical irrigation scheme connected to a reservoir of water.

C.1. Starting variables of the irrigated system

A small canal/surface irrigation scheme with a command area of 150 ha is supplied by a reservoir holding enough water to provide 500 mm of water to meet net crop water requirements (CWR, equivalent to beneficial evapotranspiration). A crop such as wheat might be irrigated with this CWR. Assuming zero contribution from rainfall, the reservoir should hold a net capacity of 750 000 cubic metres (=150 × 500 × 10). A daily net crop water requirement of 6.0 mm/day converts to a hydromodule (water duty) of 0.694 litres/second/hectare (1 mm = 10 cubic metres per hectare and one day = 86400 s). The starting design irrigation efficiency is 60%; this means the seasonal net demand converts to a gross season withdrawal of 833 mm depth equivalent (=500/0.6). The 150 ha scheme is managed by 25 farmers each with a farm of 6 ha. They share a single leadstream of 175 l/sec that rotates around whole system with an intended rotation of 10 days to provide a net dose of 60 mm (see Case 3 below). The vernacular commonly understood term ‘losses’ refers to non-beneficial evaporation, non-recovered flows and recovered flows. Total depletion refers to non-beneficial evaporation, non-recovered water and beneficial evapotranspiration. Where relevant (e.g. in Cases 8 below) 30% of ‘losses’ from this irrigated system are recovered downstream. To keep calculations simple, water withdrawals from the dam equate to water applied to the whole scheme.

C.2. Different cases of the IEM, IE and irrigation hydrology

The 13 Cases below work through some of the plausible outcomes of changes in IE according to the different dimensions and scales of the IEM.

Case 1, fraction accounting of irrigation hydrology. Applying science dimension E from a perspective of scales 3–4, the final fractions of the withdrawn irrigation water can be calculated. These can be expressed in depth equivalents (i.e. millimetres, mm) or volumes in million cubic metres (MCM). Assuming the dam is emptied over the growing season, the total gross water withdrawn is 833 mm (1.25 MCM), the beneficial evapotranspiration is 500 mm (0.75 MCM) and total ‘losses’ are 333 mm (0.5 MCM). Of the losses, the recovered flows are 100 mm (0.15 MCM) and the non-recovered fraction and non-beneficial evaporation together are 233 mm (0.35 MCM). Thus, a total of 733 mm (or 1.10 MCM) of water is depleted (=500 mm net evapotranspiration plus 233 mm of the non-returned and evaporation fractions, which are 70% of all 333 mm losses).

Case 2, designing the dam, main canal and water duty. Using the design motive of dimension D in scales 2–3 of the IEM, an irrigation efficiency of 60% means that a net irrigation volume in the dam of 0.75 MCM to supply a seasonal requirement of 500 mm will have to store at least 1.25 MCM to cover all losses and provide 833 mm to 150 ha. The design classical irrigation efficiency of 60% means that the gross hydromodule is 1.157 l/s/ha (=0.694/0.6) which converts to a 24-hour irrigation supply and main canal design of 174 l/sec (1.157 × 150), rounded up to 175 l/s.

Case 3, calculating irrigation agronomy and scheduling. A combination of motives 2 and 4 in dimension D (operation and agronomy) applied to scales 1–3 reveals the use of classical IE. The crop requires approximately 500 mm transpiration over its season. Given the scheme’s soil physics and field design, the irrigation system has to provide a net dose of 60 mm per irrigation which gets run down at 6.0 mm/day evapotranspiration over 10 days. (However the scheduling interval of 10 days will be longer when the crop is young and at the end of the season when it is starting to mature). Assuming the first 'wetting up' irrigation is 85 mm depth (because of dry and recently prepared soil), this gives seven remaining 60 mm irrigations for the crop season. With a 60% system efficiency, the dam has to release 142 mm of water to cover the first 85 mm, and 100 mm to cover the subsequent 60 mm doses. These equate to 0.15 MCM and 0.2125 MCM respectively.

Case 4, timing the leadstream rotation around the farms. Similar to Case 3, the operation and agronomy motives of dimension D in scales 1–3 place a particular emphasis on the connections between classical IE, the timing of irrigation scheduling and crop productivity, especially on gravity/canal systems where farmers rotate an irrigation supply. The equation 'time of irrigation (hours) = (mm × ha)/(l/s × IEc × 0.36)' shows that the required 10 day (240 hrs) interval to resupply the soil moisture reserve under an efficiency of 60% drops to 13 days (320 hrs) if the efficiency declines to a lower level of 45% (perhaps as a result of lax in-field control of water). The delay of 3 days in scheduling results in soil moisture not being readily available to crop roots and a consequent increase in crop stress leading to a relative decline in growth and biomass accumulation.

Case 5, raising IE to 'save water' in the dam. Employing dimension F in the IEM in scale 3, the group of farmers can 'save' water volumetrically in their reservoir by increasing their efficiency to reduce the water applied (withdrawn from their dam). After 30 days of irrigation under a starting efficiency of 60%, 450 000 cubic metres is withdrawn, leaving 800 000 cubic metres in the dam. By raising efficiency to 75%, withdrawals after 30 days amount to 360 000 m^3, leaving 890 000 m^3 in the dam. Thus after 30 days of irrigation, the increase in efficiency results in a difference of 90 000 m^3 'conserved' in the dam. Using irrigation hydrology appropriation accounting (explained by the paracommons), this conserved water could then be used by the proprietors/farmers themselves (see Case 11 below) or be 'allocated' to sustain environmental and societal demands elsewhere.

Case 6, raising IE to 'stretch water'. Using the same premise as Case 5, but expressed in a different way, we can see how farmers might instead eke out or stretch their water supply to get through an extended drought. With an efficiency of 60%, the storage of the dam is run down to zero after 83 days of continuous withdrawal of water, but lasts 104 days with a higher IE of 75%. In both cases the total volume of water withdrawn from the dam is the same, but further calculations for consumption should carefully determine the boundaries of the system (see below cases).

Case 7, inability to irrigate net crop water requirement with a lower IE. If the volume of water in the dam is fixed by design and the 25 farmers continue to wish to irrigate their total command area, a decline in irrigation efficiency from the original design of 60% creates a situation of greater scale 3 system 'all losses' and a lower beneficial fraction available to the farmers. Originally, the reservoir volume of 1.25 MCM (see Case 2) covered all losses to provide 833 mm to 150 ha which in turn ensured the net requirement of 500 mm was provided. Assuming a drop in irrigation efficiency to 45%, the reservoir volume of 1.25 MCM applied to 150 ha is 'split' into a beneficial fraction of 375 mm and total losses of 458 mm. The impact of delivering 375 mm to the farmers expecting 500 mm would be seen in reduced crop production either by farmers ceasing to irrigate some of their fields or via greatercrop-water stress.

Case 8, recovering irrigation losses across nested scales. By referring to the basin scale 4 in the IEM and an understanding of the fates of recovered losses from an irrigation system, it is possible to calculate the outcome of recovered losses picked up by a downstream irrigation system. If we assume that 30% of the losses from the farmers' scheme are recovered, then using the same starting variables and calculations for irrigation need, these returned flows would amount to 150 000 m^3 which for a gross irrigation need of 833 mm depth feeds a downstream command area of 18 ha. This means that at the basin scale, irrigated area has increased to from 150 ha to 168 ha. In turn, water depletion goes up from 1.1 MCM from the original farmers' irrigation scheme (=150 × 733 × 10) to 1.232 MCM from both irrigation systems (=168 × 733 × 10). In paracommons terms, the 'salvaged gain' from this recoverable flow has passed to the 'immediate neighbour'.

Case 9, adjusting Case 8 with different proportions of recoverable flows. If the recovered fraction of 30% of all 'losses' were to increase to 90%, or decrease to 10% of all losses, the consequences for the total command area irrigated in Case 8 above would change. The total command area, reporting from a scale 4 point of view, is 168 ha when 30% of losses are recovered flows, but this increases to 204 ha when 90% of losses are recovered and decreases to 156 ha with only 10% of losses recovered. IE calculations of these shifts are given in Case 10.

Case 10, calculating the effective irrigation efficiency. With respect to water accounting in dimension E within Scale 4, we can calculate the effective irrigation efficiency (IEe) of Cases 8 and 9. Two methods allow for cross-checking and show that the IEe, which accounts for recovered losses, is 68%, is higher than the classical irrigation efficiency of 60%. The first method uses 'depth equivalents'; it divides the net beneficial evapotranspiration of 500 mm by the total depletion of 733, giving an IEc of 68%. The second method uses water volumes; it divides the net beneficial evapotranspiration of the whole 168 ha of both systems (given in Case 8) by the total depletion for both systems (=0.84 MCM/1.232 MCM = 68%). With respect to Case 9, while the classical irrigation efficiency remains 60% across all three scenarios, the effective IE shifts from 68% (when 30% of losses are recovered) to 94% (when 90% losses are recovered) to 63% (when 10% of losses are recovered).

Case 11, expanding irrigated area within one scale. Applying the IEM's reflections on savings and water distribution within scale 3, we can see how farmers might expand their areal production by increasing their efficiency. This shift recognises that the command area of the scheme in this case is not fixed; thereafter there are several ways areal growth can happen depending on what is iteratively optimised. For example, areal growth might depend on how the salvaged/forestalled losses are retained, or what and how a new efficiency is reached over time, or what area is available to expand into. The starting calculations above reveal that 0.12 ha is irrigated with every 1000 cubic metres of water withdrawn from the reservoir. If the farmers can reduce their total 'losses' by 20% they will have 100 000 m^3 (=0.2 × 500 000) retained in their dam to irrigate an extra 12 ha, bringing the new total to 162 ha. The classical and effective irrigation efficiency changes from 60 and 68% respectively in the original 150 ha to 65% and 72% respectively in the new 162 ha. Taking a paracommons lens, the salvaged gain has been appropriated by the proprietors/farmers making the efficiency gain.

Case 12, shrinking the irrigated area to withdraw and deplete less water. Here, farmers each reduce their farm area by 10% resulting in a 10% reduction in total command area down to 135 ha, and consequently lower withdrawals by 10% or 0.125 MCM. Irrigation hydrology calculations can now be completed for the 135 ha, assuming the original net beneficial evapotranspiration of 500 mm is required. The total gross water withdrawn is 833 mm (1.125 MCM), the beneficial evapotranspiration is 500 mm (0.675 MCM) and total 'losses' are 333 mm (0.45 MCM). Of the losses, the recovered flows are 100 mm (0.135 MCM) and the non-recovered fraction and non-beneficial evaporation together are 233 mm (0.315 MCM). Thus, a total of 733 mm (or 0.990 MCM) of water is depleted. These figures show that classical and effective irrigation efficiency for the smaller irrigated area remain at 60% and 68% respectively. Appropriation accounting could then determine who gets the 0.125 MCM not withdrawn from the dam.

Case 13, voluntarily withdrawing less water. Similar to Case 12, if the farmers on the original 150 ha agree to give up 10% of their water withdrawn (0.125 MCM), but still aim to apply a net beneficial evapotranspiration depth equivalent of 500 mm to the scheme's area of 150 ha, they would have to distribute a lower volume of 1.125 MCM to all 25 farmers. This is achieved by increasing irrigation efficiency from 60% to 67%.

Other cases and scenarios. There are other ways of applying the IEM to this hypothetical irrigation scheme. Examples include:

- Another variation on Case 11 shows that the farmers could salvage their scale 3 losses to switch to a more consumptive crop e.g. maize, requiring a net evapotranspiration, of say 600 mm.
- The third way farmers can expand irrigation using conserved dam water (on the back of efficiency gains) is to 'double-crop' their land e.g. by irrigating sunflower after the wheat has been harvested.
- A calculation of irrigation efficiency from management metrics in scales 1–2 (responding to motives 2 and 4 in dimension D and shorter time scales in dimension C) during the first four weeks of the cropping season might reveal unusually low efficiencies. This is because much of the first irrigation applied to the bare fields is evaporated rather than transpired.
- Plots, fields and farms in scales 1–2 will show a spatial variation in efficiencies throughout the 150 ha depending on variable within-scheme characteristics.
- By referring to scale 5 and motive 8 in dimension D, it is possible to identify how external pressure to switch to drip irrigation might be applied by an international corporate wishing to reduce its water footprint and manage its reputation in this regard. However, by referring to 'people' in dimension B and to ways of exploring IE's technology in dimension H, one might appreciate that such wholesale technological change may fail to fully engage with how farmers may have been improving their surface/canal operations for a variety of purposes.
- Relationships between energy and water (motive 5 in dimension D applied to scales 1–3) would apply if some or all the farmers were to adopt drip irrigation run by electricity.
- The intersection of scales 2–3 and motive 7 in dimension D 'predicts' that internal social pressures could arise as farmers try to determine who benefits from and pays for 'whole system outcomes', and how material gains are appropriated to different actors.
- The use of language reveals modes of irrigation efficiency; farmers legitimately use the phrase 'saving water' in Cases 5 and 6 above (reflecting their seasonal interests applied to scales 1–3), but this can be parenthesised or qualified by taking a basin scale 4 longer-term perspective (e.g. in Cases 8 and 11) which probes the disposals of flows into final fractions and distinguishes between water applied and water consumed.
- While the four types of irrigation hydrology defined in Appendix A apply to each of the case studies above, some cases highlight the three types of hydrological accounting. Fractions accounting is revealed best in Cases 1, 8 and 10 (e.g. discerning different types of losses); management accounting is seen in Cases 3 and 4 (e.g. employing timing measures), and; appropriation accounting is seen in Cases 5 and 12 (when the final destination of salvaged water is resolved).

These simplified calculations hint at how difficult it is to fully and accurately account for water on paper, let alone 'in the real world'. The IEM cautions scientists that defining clear accounting boundaries, whilst recommended, is not easy. Irrigated systems are heterogeneous networked entities nested in scales moving through time; this means that variables and parameters constantly iterate and evolve. In other words, the outcomes of one week, month or season's irrigation activities become the starting variables for the next week, month or season (and crop-based time windows interleave rather than abut each other). Other complicating factors relate to fluxes in soil moisture over space and time arising from maturing crops, shifting rainfall patterns, and the effects of soil variability, shallow groundwater, springs and leakages from irrigation equipment. Therefore, real world accounting for irrigation hydrology requires iteration and triangulation, as well as social inquiry to agree the temporal and spatial boundaries relevant to the situation and its stakeholders.

References

ADB, 2017. Irrigation subsector guidance note: building blocks for sustainable investment. Asian Development Bank, Manila.

Ahemd, H.A., Al-Faraj, A.A., Abdel-Ghany, A.M., 2016. Shading greenhouses to improve the microclimate, energy and water saving in hot regions: A review. Sci. Hortic. 201, 36–45.

Aisenberg, I., 2017. Precision Farming Enables Climate-Smart Agribusiness. EM Compass note 46. International Finance Corporation, Washington, DC.

Alcott, B., Giampietro, M., Mayumi, K., Polimeni, J., 2012. The Jevons paradox and the myth of resource efficiency improvements. Earthscan, London.

Arnott, J.C., Neuenfeldt, R.J., Lemos, M.C., 2020. Co-producing science for sustainability: Can funding change knowledge use? Global Environ. Change 60, 101979.

Babu, A.V.S., Shanker, M., Rao, V.V., 2012. Satellite derived geospatial irrigation performance indicators for benchmarking studies of irrigation systems. Adv. Remote Sens. 1 (1), 13.

Bandara, K.M.P.S., 2003. Monitoring irrigation performance in Sri Lanka with high-frequency satellite measurements during the dry season. Agric. Water Manage. 58, 159–170.

Batchelor, C., Reddy, V.R., Linstead, C., Dhar, M., Roy, S., May, R., 2014. Do water-saving technologies improve environmental flows? J. Hydrol. 518, 140–149.

Benouniche, M., Kuper, M., Hammani, A., Boesveld, H., 2014. Making the user visible: analysing irrigation practices and farmers' logic to explain actual drip irrigation performance. Irrig. Sci. 32, 405–420.

Boelens, R., Hoogesteger, J., Swyngedouw, E., Vos, J., Wester, P., 2016. Hydrosocial territories: a political ecology perspective. Water Int. 41, 1–14.

Boelens, R., Vos, J., 2012. The danger of naturalizing water policy concepts: water productivity and efficiency discourses from field irrigation to virtual water trade. Agric. Water Manage. 108, 16–26.

Boelens, R., Vos, J., 2014. Legal pluralism, hydraulic property creation and sustainability: the materialized nature of water rights in user-managed systems. Curr. Opin. Environ. Sustainability 11, 55–62.

Bolding, A., Mollinga, P.P., Van Straaten, K., 1995. Modules for modernisation: colonial irrigation in India and the technological dimension of agrarian change. J. Dev. Stud. 31, 805–844.

BP&A, 1999 Determining a Framework, Terms and Definitions for Water Use Efficiency in Irrigation, Prepared by Barrett Purcell and Associates for the National Program for Irrigation Research and Development, Australia, p. 26.

Bos, M.G., Nugteren, J., 1990. On irrigation efficiencies, 4th ed. International Institute for Land Reclamation and Improvement (ILRI, Wageningen.

Braud, I., Fletcher, T., Andrieu, H., 2013. Hydrology of peri-urban catchments: processes and modelling. J. Hydrol. 485, 1–4.

Cai, X., Ringler, C., Rosegrant, M.W., 2001. Does efficient water management matter? Physical and economic efficiency of water use in the river basin, EPTD Discussion Paper. International Food Policy Research Institute, Washington DC, p. 55.

Cantor, A., 2017. Material, political, and biopolitical dimensions of "waste" in California water law. Antipode 49, 1204–1222.

Cash, D.W., Adger, W.N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L., Young, O., 2006. Scale and Cross-Scale Dynamics Governance and Information in a Multilevel World. Ecology and Society, p. 11.

Chicot, J., Matt, M., 2018. Public procurement of innovation: a review of rationales, designs, and contributions to grand challenges. Sci. Public Policy 45, 480–492.

Daccache, A., Ciurana, J.S., Diaz, J.A.R., Knox, J.W., 2014. Water and energy footprint of irrigated agriculture in the Mediterranean region. Environ. Res. Lett. 9, 12.

Damonte, G., Boelens, R., 2019. Hydrosocial territories, agro-export and water scarcity: capitalist territorial transformations and water governance in Peru's coastal valleys. Water Int. 44, 206–223.

de Vrese, P., Hagemann, S., Claussen, M., 2016. Asian irrigation, African rain: remote impacts of irrigation. Geophys. Res. Lett. 43, 3737–3745.

Deng, X.-P., Shan, L., Zhang, H., Turner, N.C., 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. Agric. Water Manag. 80, 23–40.

Dewulf, A., François, G., Pahl-Wostl, C., Taillieu, T., 2007. A framing approach to cross-disciplinary research collaboration experiences from a large-scale research project on adaptive water management. Ecol. Soc. 12.

Dey, P., Mishra, A., 2017. Separating the impacts of climate change and human activities on streamflow: a review of methodologies and critical assumptions. J. Hydrol. 548, 278–290.

Domínguez Guzmán, C., Verzijl, A., Zwarteveen, M., 2017. Water Footprints and 'Pozas': conversations about practices and knowledges of water efficiency. Water 9, 16.

Dumont, A., Mayor, B., López-Gunn, E., 2013. Is the rebound effect or Jevons paradox a useful concept for better management of water resources? Insights from the irrigation modernisation process in Spain. Aquat. Procedia 1, 64–76.

Edler, J., Boon, W.P., 2018. 'The next generation of innovation policy: directionality and the role of demand-oriented instruments'—Introduction to the special section. Sci. Public Policy 45, 433–434.

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B.M., Folberth, C., Foster, I., Gosling, S.N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., Olin, S., Rosenzweig, C., Ruane, A.C., Satoh, Y., Schmid, E., Stacke, T., Tang, Q., Wisser, D., 2014. Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proc. Natl. Acad. Sci. 111, 3239–3244.

FAO, 1986. Organization, operation and maintenance of irrigation schemes. FAO irrigation and drainage paper 40. In: Sagardoy, J.A., Bottrall, A., Uittenbogaard, G.O. (Eds.). FAO – Food and Agriculture Organization, Rome.

FAO, 1999. Crop Evapotranspiration, FAO Irrigation and Drainage Paper No. 56. Food and Agriculture Organisation of the United Nations (FAO), Rome.
FAO, 2017. Does Improved Irrigation Technology Save Water? A Review of the Evidence. Discussion paper on irrigation and sustainable water resources management in the Near East and North Africa. Food and Agriculture Organisation (FAO), Rome.
FAO, 2018. Water Accounting for Water Governance and Sustainable Development. Food and Agriculture Organisation (FAO) and. World Water Council (WWC), Rome, p. 53.
Fielke, S.J., Srinivasan, M.S., 2018. Co-innovation to increase community resilience: influencing irrigation efficiency in the Waimakariri Irrigation Scheme. Sustain. Sci. 13, 255–267.
Frederiksen, H.D., Allen, R.G., 2011. A common basis for analysis, evaluation and comparison of offstream water uses. Water Int. 36, 266–282.
Frederiksen, H.D., Allen, R.G., Burt, C.M., Perry, C.Responses to Gleick, et al., 2012. Responses to Gleick et al., which was itself a response to Frederiksen and Allen. Water Int. 37 (2), 183–197.
Garrick, D., Siebentritt, M.A., Aylward, B., Bauer, C.J., Purkey, A., 2009. Water markets and freshwater ecosystem services: Policy reform and implementation in the Columbia and Murray-Darling Basins. Ecol. Econ. 69, 366–379.
GCA, 2019. Adapt now: A global call for leadership on climate resilience. Global Centre on Adaptation and World Resources Institute, p. 90.
Gibson, C.C., Ostrom, E., Ahn, T.K., 2000. The concept of scale and the human dimensions of global change: a survey. Ecol. Econ. 32, 217–239.
Giordano, M., Turral, H., Scheierling, S., Tréguer, D., McCornick, P., 2017. Beyond "More Crop per Drop": Evolving thinking on agricultural water productivity. IWMI Research Report 169, Colombo, Sri Lanka: Washington, DC, USA, p. 53.
Giupponi, C., Gain, A.K., Farinosi, F., 2018. Spatial Assessment of Water Use Efficiency (SDG Indicator 6.4.1) for Regional Policy Support. Front. Environ. Sci. 6.
Gleick, P.H., Christian-Smith, J., Cooley, H., 2011. Water-use efficiency and productivity: rethinking the basin approach. Water Int. 36, 784–798.
Gober, P., 2018. Why is uncertainty a game changer for water policy and practice? In: Gober, P. (Ed.), Building Resilience for Uncertain Water Futures. Springer International Publishing, Cham, pp. 37–60.
Gómez, C.M., Pérez-Blanco, C.D., 2014. Simple myths and basic maths about greening irrigation. Water Resour. Manage. 28, 4035–4044.
Gosling, S.N., Arnell, N.W., 2016. A global assessment of the impact of climate change on water scarcity. Clim. Change 134, 371–385.
Grafton, R.Q., Williams, J., Perry, C.J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S.A., Wang, Y., Garrick, D., Allen, R.G., 2018. The paradox of irrigation efficiency. Science 361, 748–750.
Green, T.R., Yu, Q., Ma, L., Wang, T.-D., 2010. Crop water use efficiency at multiple scales. Agric. Water Manage. 97, 1099–1101.
Guijt, I., Thompson, J., 1994. Landscapes and livelihoods: environmental and socioeconomic dimensions of small-scale irrigation. Land Use Policy 11, 294–308.
Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. 111, 3251–3256.
Haie, N., 2020. Transparent Water Management Theory: Efficiency in Sequity. Springer, Singapore.
Hammani, A., Ameur, F., Kuper, M., 2017. Unraveling the enduring paradox of increased pressure on groundwater through efficient drip irrigation. In: Venot, J-P., Kuper, M., Zwarteveen, M. (Eds.), Drip Irrigation for Agriculture. Routledge, pp. 85–104.
Harrington, L., Cook, S.E., Lemoalle, J., Kirby, M., Taylor, C., Woolley, J., 2009. Cross-basin comparisons of water use, water scarcity and their impact on livelihoods: present and future. Water Int. 34, 144–154.
Hepworth, N., Orr, S., 2013. Corporate water stewardship: New paradigms in private sector water engagement. In: Lankford, B., Bakker, K., Zeitoun, M., Conway, D. (Eds.), Water security: Principles, perspectives and practices. Earthscan, Abingdon, pp. 220–238.
Hess, T.M., Knox, J.W., 2013. Water savings in irrigated agriculture A framework for assessing technology and management options to reduce water losses. Outlook Agric. 42, 85–91.
Hoffman, G.J., Howell, T.A., Solomon, K.H., 1990. Management of Farm Irrigation Systems. American Society of Agricultural Engineers, St.Joseph, Mich.
Hope, R.A., Gowing, J.W., Jewitt, G.P.W., 2008. The contested future of irrigation in African rural livelihoods – analysis from a water scarce catchment in South Africa. Water Policy 10, 173–192.
Jackson, T.M., Khan, S., Hafeez, M., 2010. A comparative analysis of water application and energy consumption at the irrigated field level. Agric. Water Manag. 97, 1477–1485.
Jensen, M., 1980. Design and operation of farm irrigation systems. ASAE Monograph No. 3. Amer. Soc. Agric. Engr. St. Joseph, MI, 829.
Jensen, M.E., 1983. Design and operation of farm irrigation systems, An ASAE monograph; No. 3, Rev. print. ed. American Society of Agricultural Engineers, St. Joseph, Mich., p. 829.
Jensen, M.E., 2007. Beyond irrigation efficiency. Irrig. Sci. 25, 233–245.
Karimov, A., Molden, D., Khamzina, T., Platonov, A., Ivanov, Y., 2012. A water accounting procedure to determine the water savings potential of the Fergana Valley. Agric. Water Manage. 108, 61–72.
Karrou, M., Oweis, T., El Enein, R.A., Sherif, M., 2012. Yield and water productivity of maize and wheat under deficit and raised bed irrigation practices in Egypt. Afr. J. Agric. Res. 7, 1755–1760.
Keller, A.A., Seckler, D.W., Keller, J., 1996. Integrated Water Resource Systems: Theory and Policy Implications. International Irrigation Management Institute, Colombo, Sri Lanka.
Knox, J.W., Kay, M.G., Weatherhead, E.K., 2012. Water regulation, crop production, and agricultural water management—Understanding farmer perspectives on irrigation efficiency. Agric. Water Manage. 108, 3–8.
Konar, M., Evans, T.P., Levy, M., Scott, C.A., Troy, T.J., Vörösmarty, C.J., Sivapalan, M., 2016. Water resources sustainability in a globalizing world: who uses the water? Hydrol. Process. 30, 3330–3336.
Kuper, M., Venot, J-P., Zwarteveen, M., 2017. Introduction: Panda or Hydra? The untold stories of drip irrigation. In: Venot, J-P., Kuper, M., Zwarteveen, M. (Eds.), Drip Irrigation for Agriculture. Untold Stories of Efficiency, Innovation and Development. Earthscan, Routledge., Oxford and New York, pp. 1–15.
Lankford, B., 2006. Localising irrigation efficiency. Irrig. Drainage 55, 345–362. https://doi.org/10.1002/ird.270.
Lankford, B., 2012a. Fictions, fractions, factorials and fractures; on the framing of irrigation efficiency. Agric. Water Manage. 108, 27–38.
Lankford, B., 2012b. Preface; Towards a political ecology of irrigation efficiency and productivity. Agric. Water Manage. 108, 1–2.
Lankford, B., 2013. Resource Efficiency Complexity and the Commons: The Paracommons and Paradoxes of Natural Resource Losses. Wastes and Wastages, Routledge, Abingdon.
Lankford, B.A., 1992. The use of measured water flows in furrow irrigation management - a case study in Swaziland. Irrig. Drainage Systems 6, 113–128.
Lankford, B.A., 1998. Effective monitoring of canal irrigation with minimum or no flow measurement. In: Pereira, L.S., Gowing, J.W. (Eds.), Water and the Environment: Innovative Issues in Irrigation and Drainage. E & FN Spon, London, pp. 265–273.
Le Maitre, D.C., Gush, M.B., Dzikiti, S., 2015. Impacts of invading alien plant species on water flows at stand and catchment scales. AoB PLANTS 7.
Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., Scardigno, A., 2014. Improving water-efficient irrigation: Prospects and difficulties of innovative practices. Agric. Water Manage. 146, 84–94.
Lopez-Gunn, E., Zorrilla, P., Prieto, F., Llamas, M.R., 2012. Lost in translation? Water efficiency in Spanish agriculture. Agric. Water Manage. 108, 83–95.
Malek, K., Adam, J.C., Stöckle, C.O., Peters, R.T., 2018. Climate change reduces water availability for agriculture by decreasing non-evaporative irrigation losses. J. Hydrol. 561, 444–460.
Marston, L., Ao, Y., Konar, M., Mekonnen, M.M., Hoekstra, A.Y., 2018. High-resolution water footprints of production of the United States. Water Resour. Res. 54, 2288–2316.
McCartney, M.P., Whiting, L., Makin, I., Lankford, B.A., Ringler, C., 2019. Rethinking irrigation modernisation: realising multiple objectives through the integration of fisheries. Mar. Freshw. Res. 70, 1201–1210.
Meinzen-Dick, R., 2007. Beyond panaceas in water institutions. Proc. Natl. Acad. Sci. 104, 15200–15205.
Mintesinot, B., Verplancke, H., Van Ranst, E., Mitiku, H., 2004. Examining traditional irrigation methods, irrigation scheduling and alternate furrows irrigation on vertisols in northern Ethiopia. Agric. Water Manag. 64, 17–27.
Molden, D.J., Sakthivadivel, R., Keller, J., 2001. Hydronomic Zones for Developing Basin Water Conservation Strategies. In: Research Report, 56. International Water Management Institute, Colombo, Sri Lanka, Colombo, Sri Lanka.
Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: Between optimism and caution. Agric. Water Manage. 97, 528–535.
Molle, F., Mollinga, P.P., Wester, P., 2009. Hydraulic bureaucracies and the hydraulic mission: flows of water, flows of power. Water Alternatives 2, 328–349.
Molle, F., Tanouti, O., 2017. Squaring the circle: Agricultural intensification vs. water conservation in Morocco. Agric. Water Manage. 192, 170–179.
Nadal-Romero, E., Cammeraat, E., Serrano-Muela, M.P., Lana-Renault, N., Regüés, D., 2016. Hydrological response of an afforested catchment in a Mediterranean humid mountain area: a comparative study with a natural forest. Hydrol. Process. 30, 2717–2733.
Nastiti, A., 2015. From MDGS to SDGS: What will it take? Towards sustainable and safe water supply for all. In: The Third Joint Seminar of Japan and Indonesia Environmental Sustainability and Disaster Prevention (3rd ESDP-2015), Institut Teknologi Bandung, Indonesia – November 25th, 2015.
Newborne, P., Dalton, J., 2016. Water Management and Stewardship: Taking Stock of Corporate Water Behaviour. UK, IUCN and ODI, Gland, Switzerland and London, p. 132.
Norris, J., 2011. Montana v. Wyoming: is water conservation drowning the Yellowstone River Compact. U. Denv. Water L. Rev. 15, 189.
Ortega-Reig, M., Palau-Salvador, G., Cascant i Sempere, M.J., Benitez-Buelga, J., Badiella, D., Trawick, P., 2014. The integrated use of surface, ground and recycled waste water in adapting to drought in the traditional irrigation system of Valencia. Agric. Water Manage. 133, 55–64.
Ortega-Reig, M., Sanchis-Ibor, C., Palau-Salvador, G., García-Mollá, M., Avellá-Reus, L., 2017. Institutional and management implications of drip irrigation introduction in collective irrigation systems in Spain. Agric. Water Manage. 187, 164–172.
Ostrom, E., 2007. A diagnostic approach for going beyond panaceas. Proc. Natl. Acad. Sci. 104, 15181–15187.
Pahl-Wostl, C., Kabat, P., Möltgen, J., 2008. Adaptive and integrated water management: Coping with Complexity and Uncertainty, Coping with Complexity and Uncertainty. Berlin und Heidelberg, Springer, Berlin, Heidelberg.
Perry, C., 2011. Accounting for water use: terminology and implications for saving water and increasing production. Agric. Water Manage. 98, 1840–1846.
Petrone, K.C., Hughes, J.D., Van Niel, T.G., Silberstein, R.P., 2010. Streamflow decline in southwestern Australia, 1950–2008. Geophys. Res. Lett. 37.
Piedelobo, L., Ortega-Terol, D., Del Pozo, S., Hernández-López, D., Ballesteros, R., Moreno, M.A., Molina, J.-L., González-Aguilera, D., 2018. HidroMap: a new tool for

irrigation monitoring and management using free satellite imagery. ISPRS Int. J. Geo-Inf. 7, 220.
Playán, E., Mateos, L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Water Manage. 80, 100–116.
Pousa, R., Costa, M.H., Pimenta, F.M., Fontes, V.C., Brito, V.F.A.d., Castro, M., 2019. Climate change and intense irrigation growth in Western Bahia, Brazil: the urgent need for hydroclimatic monitoring. Water 11, 933.
Princen, T., 2003. Principles for sustainability: from cooperation and efficiency to sufficiency. Global Environ. Polit. 3, 33–50.
Reinders, F.B., van der Stoep, I., Backeberg, G.R., 2013. Improved efficiency of irrigation water use: A South African framework. Irrig. Drain. 62, 262–272.
Renault, D., Facon, T., Wahaj, R., 2007. Modernizing irrigation management - the MASSCOTE approach. Mapping System and Services for Canal Operation Techniques, FAO Irrigation and Drainage Paper Vol. 63. Food and Agriculture Organization of the United Nations, Rome.
Rosegrant, M.W., Cline, S.A., 2003. Global food security: challenges and policies. Science 302, 1917–1919.
Rosegrant, M.W., Koo, J., Cenacchi, N., Ringler, C., Robertson, R.D., Fisher, M., Cox, C. M., Garrett, K., Perez, N.D., Sabbagh, P., 2014. Food security in a world of natural resource scarcity: the role of agricultural technologies. International Food Policy Research Institute, Washington DC.
Rudebeck, T., 2019. Corporations as Custodians of the Public Good? Exploring the Intersection of Corporate Water Stewardship and Global Water Governance, Springer, Cham, Switzerland.
Sadoff, C.W., Borgomeo, E., Uhlenbrook, S., 2020. Rethinking water for SDG 6. Nat. Sustainability 3, 346–347.
Sawicz, K.A., Kelleher, C., Wagener, T., Troch, P., Sivapalan, M., Carrillo, G., 2014. Characterizing hydrologic change through catchment classification. Hydrol. Earth Syst. Sci. 18, 273–285.
Scheierling, S.M., Young, R.A., Cardon, G.E., 2006. Public subsidies for water-conserving irrigation investments: Hydrologic, agronomic, and economic assessment. Water Resour. Res. 42.
Scholes, R.J., Reyers, B., Biggs, R., Spierenburg, M.J., Duriappah, A., 2013. Multi-scale and cross-scale assessments of social–ecological systems and their ecosystem services. Curr. Opin. Environ. Sustainability 5, 16–25.
Scott, C.A., Vicuna, S., Blanco-Gutierrez, I., Meza, F., Varela-Ortega, C., 2014. Irrigation efficiency and water-policy implications for river basin resilience. Hydrol. Earth Syst. Sci. 18, 1339–1348.
Seckler, D., W, Molden, D., Sakthivadivel, R, 2003. The concept of efficiency in water-resources management and policy. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Development. CAB International, Wallingford, pp. 37–51.
Seckler, D.W., 1996. The new era of water resources management : from "dry" to "wet" water savings. International Irrigation Management Institute, Colombo, Sri Lanka.
Senyolo, M.P., Long, T.B., Blok, V., Omta, O., 2018. How the characteristics of innovations impact their adoption: An exploration of climate-smart agricultural innovations in South Africa. J. Cleaner Prod. 172, 3825–3840.
Sese-Minguez, S., Boesveld, H., Asins-Velis, S., Van der Kooij, S., Maroulis, J., 2017. Transformations accompanying a shift from surface to drip irrigation in the Cànyoles Watershed, Valencia, Spain. Water Altern. 10, 81–99.
Shah, T., Anwar, A.A., Amarasinghe, U.A., Hoanh, C.T., Reddy, J.M., Molle, F., Mukherji, A., Prathapar, S.A., Suhardiman, D., Qureshi, A.S., 2012. Canal irrigation conundrum: applying contingency theory to irrigation system management in India. In: IWMI-Tata Water Policy Research Highlight No, 25. International Water Management Institute, Colombo, Sri Lanka.
Simons, G.G., Bastiaanssen, W.W., Immerzeel, W.W., 2015. Water reuse in river basins with multiple users: a literature review. J. Hydrol. 522, 558–571.
Srinivasan, M., Bewsell, D., Jongmans, C., Elley, G., 2017. Just-in-case to justified irrigation: applying co-innovation principles to irrigation water management. Outlook Agric. 46, 138–145.
Steduto, P., Hoogeveen, J., Winpenny, J., Burke, J., 2017. Coping with water scarcity: an action framework for agriculture and food security. Food and Agriculture Organization of the United Nations Rome.
Swyngedouw, E., 2009. The political economy and political ecology of the hydro-social cycle. J. Contemporary Water Res. Educ. 142, 56–60.
Trompette, P., Vinck, D., 2009. Revisiting the notion of Boundary Object. Revue d'anthropologie des connaissances 3 (1), 3–25.
Trottier, J., Perrier, J., 2018. Water driven Palestinian agricultural frontiers: the global ramifications of transforming local irrigation. J. Polit. Ecol. 25, 292–311.
UN, (2017) The Sustainable Development Goals Report. United Nations, New York.
van der Bliek, J., McCornick, P., Clarke, J., 2014. On target for people and planet: setting and achieving water-related sustainable development goals. International Water Management Institute (IWMI), Colombo, Sri Lanka.
van der Kooij, S., Kuper, M., de Fraiture, C., Lankford, B., Zwarteveen, M., 2017. Re-allocating yet-to-be-saved water in irrigation modernization projects. the case of the Bittit Irrigation System. Morocco. In: Venot, J-P., Kuper, M, Zwarteveen, M (Eds.), Drip Irrigation for Agriculture. Untold Stories of efficiency, innovation and development. Earthscan, Routledge, Oxford, UK, pp. 68–84.
van Dijk, A., Evans, R., Hairsine, P., Khan, S., Nathan, R., Paydar, Z., Viney, N., Zhang, L., 2006. Risks to the shared water resources of the Murray-Darling Basin. MDBC Publication 22/06. Murray-Darling Basin Commission, Canberra.
Van Halsema, G.E., Vincent, L., 2012. Efficiency and productivity terms for water management: a matter of contextual relativism versus general absolutism. Agric. Water Manage. 108, 9–15.
van Rooyen, A.F., Moyo, M., Bjornlund, H., Dube, T., Parry, K., Stirzaker, R., 2020. Identifying leverage points to transition dysfunctional irrigation schemes towards complex adaptive systems. Int. J. Water Resour. Dev. 1–28.
Vanham, D., Hoekstra, A.Y., Wada, Y., Bouraoui, F., de Roo, A., Mekonnen, M.M., van de Bund, W.J., Batelaan, O., Pavelic, P., Bastiaanssen, W.G.M., Kummu, M., Rockström, J., Liu, J., Bisselink, B., Ronco, P., Pistocchi, A., Bidoglio, G., 2018. Physical water scarcity metrics for monitoring progress towards SDG target 6.4: An evaluation of indicator 6.4.2 "Level of water stress". Sci. Total Environ. 613–614, 218–232.
Venot, J-P., 2017. From obscurity to prominence. How drip irrigation conquered the world. In: Venot, J-P., Kuper, M., Zwarteveen, M. (Eds.), Drip Irrigation for Agriculture. Untold Stories of efficiency, innovation and development. Earthscan, Routledge, pp. 16–37.
Venot, J-P., Kuper, M., Zwarteveen, M., 2017. Drip irrigation for agriculture: untold stories of efficiency, innovation, and development. Routledge, Abingdon.
Vermillion, D.L., 2005. Irrigation sector reform in Asia: From participation with patronage to empowerment with accountability. In: Shivakoti, G.P., Vermillion, D.L., Lam, W.F., Ostrom, E. (Eds.), Asian irrigation in transition: Responding to challenges. SAGE Publications, New Delhi, pp. 409–436.
Vos, J., Marshall, A., 2017. Conquering the desert. In: Venot, J-P., Kuper, M., Zwarteveen, M. (Eds.), Drip Irrigation for Agriculture. Untold Stories of efficiency, innovation and development. Earthscan, Routledge, Abingdon, pp. 134–150.
Vos, J., van Oel, P., Hellegers, P., Veldwisch, G.J., Hoogesteger, J., 2019. Four perspectives on water for global food production and international trade: incommensurable objectives and implications. Curr. Opin. Environ. Sustainability 40, 30–36.
Wallender, W.W., Grismer, M.E., 2002. Irrigation hydrology: crossing scales. J. Irrig. Drain. Eng. 128, 203–211.
Ward, F.A., 2014. Economic impacts on irrigated agriculture of water conservation programs in drought. J. Hydrol. 508, 114–127.
Ward, F.A., Pulido-Velázquez, M., 2008. Water conservation in irrigation can increase water use. Proc. Natl. Acad. Sci. 105, 18215–18220.
Wesseling, J.H., Edquist, C., 2018. Public procurement for innovation to help meet societal challenges: a review and case study. Sci. Public Policy 45, 493–502.
Wheeler, S.A., Carmody, E., Grafton, R.Q., Kingsford, R.T., Zuo, A., 2020. The rebound effect on water extraction from subsidising irrigation infrastructure in Australia. Resour. Conserv. Recycl. 159, 104755.
Wichelns, D., 2015. Virtual water and water footprints: overreaching into the discourse on sustainability, efficiency, and equity. Water Alternatives 8.
Wichelns, D., 2017. The water-energy-food nexus: Is the increasing attention warranted, from either a research or policy perspective? Environ. Sci. Policy 69, 113–123.
Willardson, L., Allen, R., Frederiksen, H., (1994) Elimination of irrigation efficiencies. In: 13th Technical Conference. USCID, Denver, Colorado, pp. 19–22.
Woodhouse, P., 2012. Foreign Agricultural Land Acquisition and the Visibility of Water Resource Impacts in Sub-Saharan Africa. Water Alternatives 5.
Woodhouse, P., Veldwisch, G.J., Venot, J.-P., Brockington, D., Komakech, H., Manjichi, Â., 2017. African farmer-led irrigation development: re-framing agricultural policy and investment? J. Peasant Stud. 44, 213–233.
Zhang, L., Zhao, F., Brown, A., 2012. Predicting effects of plantation expansion on streamflow regime for catchments in Australia. Hydrol. Earth Syst. Sci. 16, 2109–2121.
Zimmerer, K.S., 2011. The landscape technology of spate irrigation amid development changes: Assembling the links to resources, livelihoods, and agrobiodiversity-food in the Bolivian Andes. Global Environ. Change 21, 917–934.