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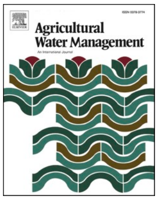

Resolving the paradoxes of irrigation efficiency: Irrigated systems accounting analyses depletion-based water conservation for reallocation

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ABSTRACT

The irrigation efficiency paradox says that raising the efficiency of irrigation systems, thereby reducing return flows, either gives no change in water depletion or it raises depletion via increased evapotranspiration and irrigated area. While this paradox can occur, there are problems associated with it. It eludes precise explanation and characterisation; it can be confused with other irrigation hydrology paradoxes; it is one of several ways irrigated areas increase; it over-emphasises the role of return flows; it relies on other irrigation variables (usually unstated) being uncontrolled; it can be inverted to reduce depletion; and it may mistakenly guide the conservation of water in irrigated systems. Addressing these concerns, a comprehensive predictive model called Irrigated Systems Accounting (ISA) analyses irrigation undergoing water conservation based on accounts for soil-crop evapotranspiration, irrigation efficiency (IE), irrigation practices and infrastructure, withdrawals, depletion, crop production and water reallocation. By using more calculi than current water accounting, ISA; resolves irrigation efficiency paradoxes; predicts how an irrigated system changes its aggregate area and depletion via primary, expansion and reuse zones; and reveals how other non-IE factors drive up area but not necessarily depletion. Compiling all zonal changes reveals how reductions in aggregate depletion can be derived and reallocated to other users without cutting crop production. The paper concludes there are hazards for water policy if irrigation efficiency and depletion are exclusively tied together via imprecise characterisations that draw on water accounting models containing few terms and relationships.

1. Introduction

1.1. *On the paradoxing of irrigation efficiency*

The need for accurate water accounting and excellent management of frugal irrigation arises because of the rewards for river basins when water depleted by irrigated agriculture can be reduced to provide water to other sectors simultaneously not cutting food production (Falkenmark and Molden, 2008; Jägermeyr et al., 2017). As UN Water Sustainable Development Goal 6 implies,[1] observers often put ‘efficient irrigation’ or ‘water use efficiency’ as a solution to this task (2030WRG, 2009; Fader et al., 2015; Flörke et al., 2018; Palazzo et al., 2019; UN, 2017) despite cautions of a water depletion ‘rebound paradox’ occurring with rising irrigation efficiency (IE) (Grafton et al., 2018; Van Opstal et al., 2021; Wheeler et al., 2020). These cautions warn that programmes to conserve/reduce water withdrawn to the farm or applied at the field scale (called paper, apparent or dry savings) may bring paradoxical outcomes of; not reducing water depleted at the basin scale (called real or wet savings) (Seckler, 1996); or inducing greater water depletion; and/or increasing irrigated area (Grafton et al., 2018; Nieuwoudt and Armitage, 2004).

Accepting irrigation water conservation brings paradoxes (Lankford, 2013), this paper’s objectives are to; 1) apply a new accounting model to predict aggregate changes in area, depletion and crop production; 2) explore difficulties in characterising water conservation via a single irrigation efficiency paradox; 3) present ways of effecting depletion-based savings without cutting crop production; 4) review the design of models for water accounting; and 5) highlight policy insights. The paper argues that inaccurate water accounting and explanations are occurring across many analyses including those claiming to divine ‘real water savings’ (Van Opstal et al., 2021). This means scientists may be ‘mis-paradoxing’ irrigation both quantitatively when assessing hydrological change, and qualitatively when using terms that are insufficiently precise. This paper believes the changing agro-hydrology (Allen

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[1] UN Sustainable Development Goal Target 6: “By 2030, to substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity.”

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et al., 2005) of irrigated systems is much more diverse than described by the IE paradox literature – a point also made by Cai et al. (2023) – with consequences for how we; 1) manage crop evapotranspiration, soil moisture, irrigation and scarce water supplies; 2) balance food production with water reallocation; 3) explain and characterise water conservation options in irrigated agro-hydrology; and 4) resolve various IE paradoxes.

There are problems with framing a changing agro-hydrology via a paradox. A paradox is defined as a statement or tenet contrary to received opinion (OED, 2023). Determined by consensus, it can become a norm or an orthodoxy requiring little or no further specification. The risk is that a poorly specified paradox holds dual truths simultaneously. An irrigation system behaves as expected, yet with one or few variables changed, it behaves paradoxically, or vice versa. By not recognising this duality, a paradox changes from being a helpful caution against 'raise irrigation efficiency' calls to becoming a baked-in universal truth that raising IE in hi-tech irrigation always leads to increases in water depletion (FAO, 2017). This duality needs questioning so that diverse water management options, incorporating IE, are integrated to meet food-neutral (or positive) water reallocation goals. This paper uses 'paradox' when describing or critiquing the mainstream explanations of how changes to IE create unexpected outcomes, thereafter more precise (e.g. 'aggregate increase') or other terms ('pitfall') are employed.

Diverse water management options arise from a multitude of soil, crop, irrigation system and catchment variables and relationships operating across spatial and temporal scales. These variables and relationships need accounting for, examples of which include; soil-crop and irrigation practices (IP, e.g. deficit irrigation); irrigation infrastructure (II, e.g. large-scale storage and irrigation areas); an explicit treatment of changes in scale and time; and a need to focus on periods of water scarcity. If, however, IE and irrigated systems hydrology are treated via water accounts that have only one purpose, or use very few terms and variables, or are only interested in "sources and uses" (Perry, 2011), or play to simple maxims ('traditional irrigation systems are inefficient and leaky'; 'efficient systems deplete more water'), scientists will omit these many variables and their significance for managing water.

Thus adding variables and relationships is not only for questioning dualities and paradoxes, it is about sharpening the purpose of water accounting in water-scarce catchments to sustain or boost crop production. For example, irrigated systems are increasingly supported by non-irrigation sources of water, such as improved capture of rainfall and non-natural (unconventional) sources like wastewater, thereby decoupling irrigation from formal withdrawals of natural streamflows and aquifers (Gilmont, 2013; Li et al., 2022). Furthermore, by including more sources of water and soil-crop-water determinants (e.g. evapotranspiration (ET), rainfall and deficit irrigation), a more complete model of crop ET as a proxy for crop production, set against the depletion of formal withdrawals, can be derived.

Nonetheless, this author recognises the frustration that those upholding the significance of 'real savings' (Van Opstal et al., 2021) rightly have with the 'how to save water' literature leading to advice such as "replacing water-inefficient irrigation schemes with more efficient irrigation technologies" (Gleick and Iceland, 2018 Page 2). This is a literature that often poorly distinguishes between reductions in; 'a' water withdrawals, 'b' field water applications (whether defined by depth applied per field or volume over a farm's changing area), 'c' depletion at the farm (i.e. irrigation system) level, and 'd' depletion at the basin level. An example of this gap is found in Jovanovic et al. (2020) who, despite underscoring the need for accurate accounting of depletion in saving water, do not distinguish between depletion at the farm/system and basin scales. Without this distinction, depletion can be cut at the farm/system level but total depletion at the basin level can go up (see Sections 4.1.3 and 4.1.4).

Mentioned above, the other complication authors point to is how to find cuts in water depletion without harming crop production. Pérez-Blanco et al. (2020) term this a pareto-efficient solution or pareto improvement whereby 'no one is left worse off and at least one user is left better off'. In other words, crop production is not left worse off when reductions in water depletion are pursued to reallocate that water to other basin uses and sectors. Although there is debate about the appropriateness of a more pragmatic Kaldor–Hicks improvement (Prieto, 2021), ISA is currently guided by a pareto framing, accepting crop production should not be harmed when less water is depleted by irrigation.

A more detailed accounting model, proposed by ISA, makes these distinctions in order to compute soil-crop evapotranspiration, total water depletion and pareto-neutral water reallocation. Going further, this paper shows that the 'a, b, c, d' distinctions above are not unrelated or in opposition to each other. In other words, 'reducing withdrawals' is not the faux-pas that 'reducing depletion' protagonists state it is. ISA shows reductions in withdrawals nearly always reduce depletion. Furthermore, given paper savings and reductions in withdrawals are arguably the same,[2] this paper recommends that 'paper savings', with its confusions (see Appendix A Section 3.6.3) and connotation of irrelevance, is replaced by other terminology, e.g. 'withdrawal reductions'.

This paper does not question the premise that under certain circumstances an increase in beneficial water evapotranspiration paradoxically follows an increase in IE; a phenomenon explained by the limited composition of the IE ratio (Ward and Pulido-Velázquez, 2008).[3] Paradoxes arise because the classical IE ratio (CIE%) is unable to fully articulate and control for the relevant fractions and flows within irrigation over time and space, meaning outcomes can confound expectations. However in testing this premise, this paper argues the IE ratio and water accounting (WA) calculations (Perry, 2011; Perry et al., 2023) in turn omit other variables and relationships which more accurately explain increases in total depletion and area. Thus, some explanations of the IE paradox, see for example Grafton et al. (2018), rarely connect hydrological changes to irrigation variables that sit outside of IE.

1.2. Origin and scope of the paper

The origin of this paper begins with observations about the citrus industry in South Africa. When working on drought-driven irrigation in Swaziland in the 1980s, the author visited irrigated citrus growers in Mpumalanga Province. He recalls their orchard water applications appeared highly efficient using a mix of conveyance pipes, careful dosing and scheduling, and sprinkler, micro-spray and drip irrigation. Farm and orchard water losses were carefully controlled, and occurred mostly via non-beneficial evaporation rather than as large drainage flows. (However, surface runoff arose during high rainfall events when irrigation could not be ceased at short notice). Yet in return visits in 40 years later (Lankford et al., 2023), citrus in that region has grown significantly without being becoming wholly more efficient. What is behind the growth in irrigated area if not explained by leaky inefficient systems with small areas becoming consumptive efficient modern systems with large areas? Two answers computed by ISA are; 1) a greater use of in-situ, informal and hidden water; and 2) the conversion of the non-beneficial consumption and non-recovered fractions (but not recovered flows) to beneficial consumption.

The present paper is supported by 'Irrigated Systems Accounting' (ISA). ISA is a water accounting model that utilises irrigation efficiency, practice and infrastructure variables and relationships operating in three irrigation zones over spatial and time scales to quantify agro-hydrology,

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[2] A cut in field-level irrigation applications is another interpretation of 'paper savings'. ISA can calculate the differences between withdrawals at the intake and field-level applications – see Appendix A for this discussion.

[3] Since CIE = BC/(BC + losses) or CIE = BC/(withdrawals), CIE goes up if losses reduce relative to withdrawals, or CIE can go up if BC is increased relative to withdrawals, or CIE can go up if BC is increased relative to losses.

soil moisture evapotranspiration, irrigation, other water supplies, food production and depletion-based re-allocation of water. This model works with conventional or 'natural' (Gilmont, 2013) withdrawn water during water-scarce periods excluding wetter months when irrigation and reallocation may not be needed. Emphasising irrigated systems, this paper does not study the water accounting of basins comprising different water sectors where other accounting models may be appropriate (Bassi et al., 2020; Karimi et al., 2013). To create and test ISA, an Excel model was constructed (Appendix B) which adopted a standard Excel design. Rows give variables and calculations, and columns represent different scenarios including a baseline case (Time 1, before or without changes) and Time 2 cases (T2, after or with changes to variables). This allows modellers to compute change over time (such as savings) and to adjust variables to create and explain new cases and scenarios.

The paper also discusses how designs of hydrological accounting models inform water science. For the purposes of this paper, these models are either 'descriptive-explanatory' or 'predictive' (Hobbs and Morton, 1999; Shmueli, 2010). WA as a framework or schema, expressed in various articles (Perry, 2011; Perry et al., 2023), is more descriptive-explanatory because, while it can retrospectively explain agro-hydrological change, it omits many variables and relationships needed to predict outcomes at different scales. ISA is more predictive because it uses multiple variables and relationships to calculate hydrological, areal and crop production outcomes. This difference between ISA and WA may seem inconsequential, but the design of models becomes relevant if we aim to predict food-neutral reductions in total water depletion that do not add to local energy needs, and other costs and externalities (although currently ISA does not address energy).

1.3. Building on water accounting (WA)

ISA builds on important insights of water accounting (WA) including its conceptualisation of water fractions, flows or dispositions (Perry, 2011; Willardson et al., 1994). In WA, irrigation withdrawals (IW) flowing into an irrigation system divide into four different water dispositions. These are the; beneficial consumption of water in crop evapotranspiration (BC); non-beneficial consumption (NBC as evaporation); recovered[4] flows (RF); and non-recovered flows (NRF). Fig. A2 in Appendix A illustrates these, noting that storage is a temporary (fifth) option.

While internally valid as a four-part sum of the final dispositions of withdrawn water, WA lacks other key variables and relationships covered in Section 2.2 below. Some of these gaps include; other ways of replenishing soil moisture; incorporating different scales and zones; using efficiency ratios to distribute withdrawals to more than four dispositions; mathematically calculating before and after scenarios to derive simultaneous changes in area, depletion and crop production; and including catchment supply and non-withdrawn water as accounting flows.

1.4. What is irrigation?

A new approach to irrigation water accounting reflects on the question 'what is irrigation? The WA model is a conservative or modest answer; irrigation is the 'ins' of water withdrawal and the 'outs' of beneficial consumption and return flows (Perry et al., 2023; see page 9). But irrigation is much more than this. It is the changing collation of different sources of water by farmers seeking to apportion, usually imperfectly, flows and volumes to match soil/crop demands changing over time and space within an irrigation system comprising social, physical and environmental constraints also changing over time and space. Put like this, modelling irrigation requires many variables and relationships.

Furthermore, driven to innovate under increasing pressures (Sutcliffe et al., 2021), irrigation is evolving. Take how rainfall and irrigation connect. In a basic way, a lack of rainfall is why irrigation is needed. This might explain why withdrawals act as the starting point for WA, but beyond that rainfall is not actively interwoven into the accounts of WA.[5] Yet consider how rainfall and irrigation work together in irrigation systems. When the amount of effective rainfall stored in the soil is increased (e.g. by terracing) this does not only alter the sum of the amount of irrigation needed, it provides options to combine rainfall and irrigation in different ways. One is to reduce the amount of irrigation water withdrawn and applied, while another is to continue with the same withdrawals to extend the area irrigated. Here, when farmers manage their soils to capture more rainfall, rather than this 'using less water' (Lal, 2020) it uses the same water to paradoxically increase the irrigated area.

Similarly, water storage is more than an intermediate stage between withdrawals and dispositions. Storage offers options of managing water volumes and timings alongside scarce seasonal water. If stored water adds to withdrawn water, irrigated areas increase; but if stored water replaces water withdrawals, it can reduce the latter's depletion and lower the impact of irrigation on its catchment (McCartney and Smakhtin, 2010). These and other ways of managing crops, land and-water suggest a more comprehensive approach to water accounting is needed.

2. Method: Irrigated Systems Accounting

2.1. Introduction

Table 1 presents the abbreviations employed in ISA. Appendix A reproduces this table, explains the definitions, and contains a conceptual framework that guides Section 2. A few preliminary notes are relevant at this point. The terms 'catchment', 'river basin' and 'basin' are used interchangeably. ISA uses 'depletion' rather than 'consumption' (Karimi et al., 2013). Depleted water is no longer available for productive use by any party, although non-recovered water can generate benefits, e.g. sinks used by wildlife. ISA can compute the depletion of withdrawn water from surface- and groundwater, however only surface water is assessed in the current version. ISA focusses on scarce-season hydrology where demand matches or exceeds supply and where water reallocation is needed. Following Van Opstal et al. (2021), ISA defines paper or apparent savings as reductions in withdrawals rather than reductions in field water applications (see discussion in Appendix A, Section 6.3.6).

2.2. The ISA hydrological model

Fig. 1 is a depiction of the hydrological model of ISA giving the arrangement and types of water flows and dispositions into and out of an irrigated system. The 12 sub-sections below describe these and the important functions and objectives of ISA.

2.2.1. Spatial and time scales

Drawing on Lankford et al. (2020), ISA accounts for agro-hydrological change over both spatial and time scales. ISA expresses agro-hydrology as scalar ('within-scale', 'cross-scale') and time-defined ('within time' and 'over time'). Within-scale occurs when a field, farm or irrigation system expands its own irrigated area in the same level or scale. Thus, a farmer irrigates a farm of 1.5 ha one year but expands this to 1.7 ha two years later by adopting different irrigation practices and infrastructure. Cross-scale means an outflow lost from a

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[4] This paper generally uses the more definite adjective 'recovered' rather than the possibility adjective of 'recoverable'. (Just as WA uses withdrawn or consumed water rather than withdrawable or consumable water).

[5] The lack of rainfall in WA was questioned by Bart Snellen, reported in Perry (2011).

Table 1
Main abbreviations employed in ISA.

AAKc	Average areal crop factor	NWW	Non withdrawn water
ABU	Additional beneficial uses	OWBC	Other water beneficial consumption
ADC	Aggregate depletion change	Pr	Proprietor
ADI	Aggregate depletion impact	Pe	Effective rainfall
ADWR	Aggregate depletion withdrawal ratio	PEDL	Primary + expansion depleted losses
AWD	Aggregate water depletion	PENBC	Primary + expansion non-beneficial consumption
BC	Beneficial consumption	PENIR	Primary + expansion net irrigation requirement
BL	Baseline	PENRF	Primary + expansion non-recovered fraction
BSW	Baseline season withdrawal	PERF	Primary + expansion recovered fraction
Cg	Capillary rise	PERRF	Primary + expansion reused recovered fraction
CIE	Classical irrigation efficiency	PEURF	Primary + expansion unused recovered fraction
CSW	Corrected season withdrawal	PEZA	Primary and expansion zone area
CWP	Crop water productivity = WUE	PEZ	Primary and expansion zone
DE	Depth equivalent (or De)	PEZFA	PEZA field applications
DIF	Deficit irrigation factor	PRW	Partial root wetting
DSS	Duration of season supply	PZ	Primary zone
Ea	Field application efficiency	PZA	Primary zone area
Ec	Conveyance efficiency	PZAL	Primary zone all losses (NBC, NRF, RF)
Ed	Distribution efficiency	PZD	Primary zone depletion
EIE	Effective irrigation efficiency	PZNIR	Primary zone net irrigation requirement
ET	Crop evapotranspiration	PZDL	Primary zone depleted losses (NBC, NRF)
$ET_{c\ act}$	Crop evapotranspiration actual	PZNBC	Primary zone non-beneficial consumption
$ET_{c\ adj}$	ETc adjusted for duration	PZNRF	Primary zone non-recovered fraction
ET_c	Crop evapotranspiration	PZFA	Primary zone field applications
ET_o	Reference crop evapotranspiration	RF	Recovered fraction (or flows)
ETM	ET modification	RFR	Recovered fraction ratio
EZ	Expansion zone	RRF	Reused recovered fraction
EZA	Expansion zone area	RRR	Reused recovered ratio
EZD	Expansion zone depletion	RSW	Required season withdrawal
FAO	Food and Agriculture Organisation	RUW	Residual unused water
FETR	Field ET reduction	RUWC	Residual unused water change
GIR	Gross irrigation requirement	RWO	Realisable water overplus
Ha	Hectares	RZ	Reuse zone
hm^3	Cubic hectometre = MCM	RZA	Reuse zone area
IAC	Irrigated area correction	RZCIE	Reuse zone CIE
ICBC	Irrigated crop beneficial consumption	RZD	Reuse zone depletion
IE	Irrigation efficiency	RZNBC	Reuse zone non-beneficial consumption
II	Irrigation infrastructure	RZNIR	Reuse zone net irrigated requirement
IP	Irrigation practice(s)	RZNRF	Reuse zone non-recovered fraction
ISA	Irrigated systems accounting	SMD	Soil moisture deficit
ISMC	Initial soil moisture content	SSS	Scarce season supply
ISW	Informal supplementary water	SSW	Scarce season withdrawal
ITC	Irrigating time correction	SSWC	Scarce season withdrawal change
ITD	Irrigating time duration	SSWR	Scarce season withdrawal ratio
IWO	Irrigation withdrawal overplus	STOR	Season storage use
IWR	Irrigation withdrawal reduction	T1	T1 is ‘time 1’. Baseline ‘before’ or ‘without’ case
IWS	Irrigation withdrawal shortfall	T2	T2 is ‘time 2’, ‘after’ or ‘with’ case
Kc	Crop factor	TBC	Total beneficial consumption
l/sec	Litres/second	TZ	Total zone
MCM	Million cubic metres = hm^3	TWW	Total water withdrawals
mm	Millimetres	TZA	Total zone area
Nb	Neighbour	TZAC	Total zone area change
NBC	Non-beneficial consumption	TZD	Total zone depletion
NIA	Net irrigated area	TZDC	Total zone depletion change
NIR	Net irrigation requirement	URF	Unused recovered fraction/flows
NRF	Non-recovered fraction (or flows)	WA	Water accounting
NS	Nature and society	WUE	Water use efficiency = CWP

field or farm ends up as an inflow to an irrigation system locally or elsewhere in the basin. Thus, drainage from the farmer irrigating 1.5 ha feeds another farm of say 0.3 ha further down the catchment. This is ‘within time’ because the recovered flow feeds the downstream farm around the same time as feeding the first-use farm. ‘Over time’ means there is a clear ‘before and after’ where ‘before’ is the baseline in Time 1 (T1) prior to changes, and ‘after’ is the Time 2 (T2) system 1–5 years later. The example farm grows from 1.5 to 1.7 ha over time, where the 1.5 ha T1 baseline farm has its own agro-hydrology (providing water for 0.3 ha downstream) but the T2 1.7 ha farm, now larger and more depletive, has a different hydrology likely providing smaller drainage flows supplying, say, only 0.1 ha downstream in T2.

2.2.2. *Three irrigation zones and the irrigated basin*

ISA accounts for water flowing into and through three irrigation zones. The primary zone (PZ) is the irrigation system that withdraws first-use water from which WA dispositions/fractions emanate. This primary zone can expand over time within-scale to a second type called an expansion zone (EZ).[6] Third, is the reuse zone of irrigation (RZ), fed by local or non-local cross-scale recovered losses from the combined primary and expanded zone. These three zones make up the total zone

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[6] Expansion occurs by using water; a) from the existing main intake distributed via the conveyance and distribution canals and pipes; or b) from new water distribution infrastructure. Expanded areas are found in enlarged fields, or via newly added farms and fields.

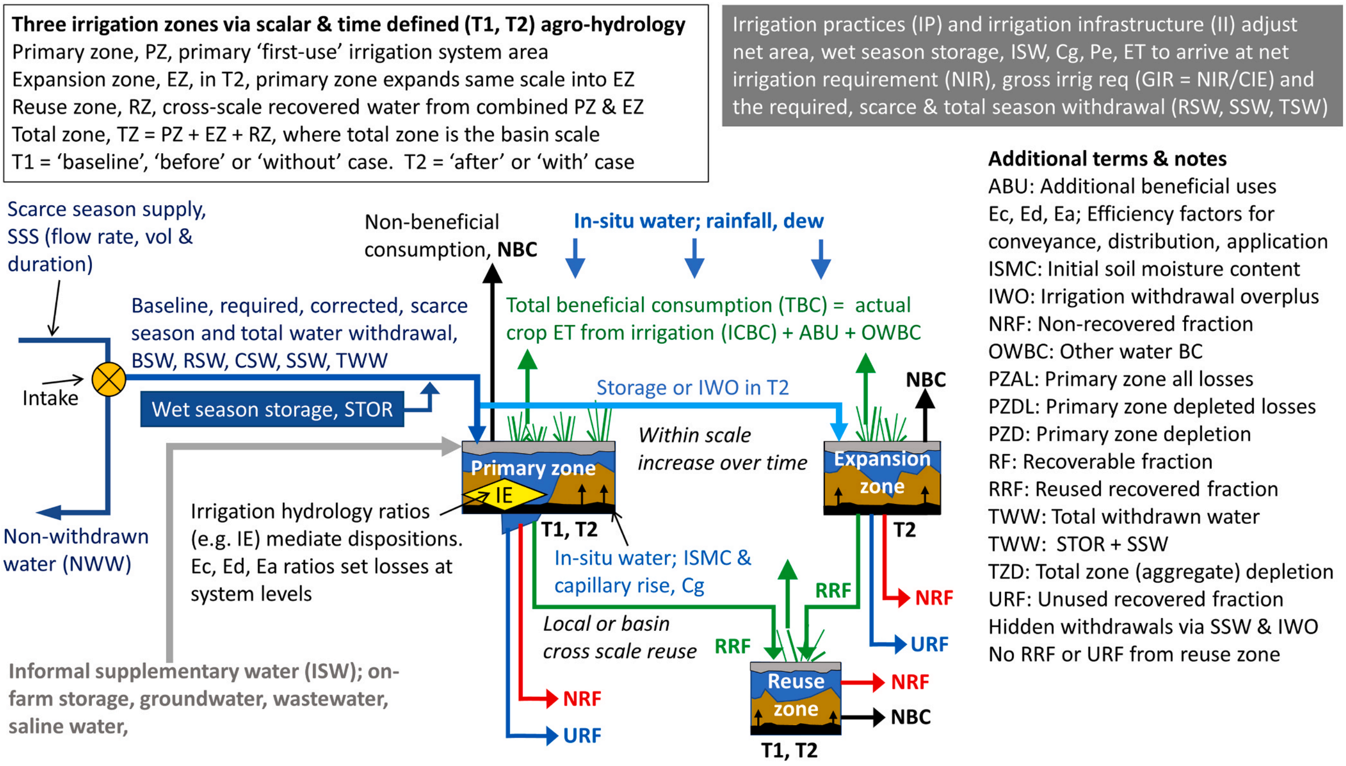

Fig. 1. The hydrological model of ISA.

(TZ). ISA identifies the PZ as primary because changes to its IE, IP and II variables (e.g. crop type, CIE%, storage, etc.) leads to changes in water dispositions and therefore to changes in the expansion and reuse zones, and thus across the total zone. In the Excel model, ISA conducts accounts on the primary + expansion zone combined before separating this pro rata into the primary and expansion zones.

The total of all three zones, plus the basin's supply of water and its non-withdrawal and non-depletion (the latter two passing to nature and society (Lankford and Scott, forthcoming)) represent the basin system and scale. Three benefits of this zonal and basin-wide formulation follow. Rather than only accounting for withdrawals into an irrigation system, water accounts for an irrigated basin provide an assessment of water reallocation opportunities including who gains and loses water following water conservation. Second, per-zone metrics enable a more transparent view of how changes in zonal waters interlink and play out. Third, because ISA connects the T1 and T2 versions of the three zones and their total, it can calculate over-time aggregate changes in area, depletion, crop production and other variables.

2.2.3. *Irrigation practices and infrastructure variables*

ISA observes how, in addition to irrigation efficiency, irrigation practices and infrastructure adjust the agro-hydrology of irrigated systems. ISA utilises FAO-type irrigation calculations (FAO, 1999; Pereira et al., 2021a) to examine water management and conservation made up from irrigation efficiency (IE), practices (IP) and infrastructure (II). Irrigation practices and infrastructure include physical features such as large-scale storage, informal water from farm ponds, intake capacities, command area, and practices like deficit irrigation. All three (IE+II+IP) control hydrological flows such as the water evapotranspired and withdrawn amount of water required to irrigate the crop. Also, IE+IP+II determine how soil moisture deficits and crop ET are managed (e.g. by rainfall, capillary rise, deficit irrigation and so on). The inclusion of command area and days spent irrigating (examples of IP+II) is key because both affect agro-hydrology and allow the re-calculation of millimetre (mm) depth equivalents into water volumes. While irrigating time is less well recognised than command area, both are 'extensive margins' (Drysdale and Hendricks, 2018) for the way they adjust the irrigation depth intensive margin to derive water volumes across the three zones.

2.2.4. *Soil-crop evapotranspiration accounting*

Guided by Fig. 2, soil-crop ET accounting is pivotal to ISA's objectives because ISA identifies that crop evapotranspiration is both a proxy for crop production and, along with soil moisture, rainfall and irrigation, can be managed to sustain crop production (Section 2.2.11). The following seven paragraphs explain how soil-crop ET needs are managed and met by different types of water sources and supplies:

1) ISA manages crop ET via four stages[7], guided by Pereira et al. (2021b); Pereira et al. (2020). The overall aim of the four stages to get from the reference crop ET_o to the actual crop evapotranspiration ($ET_{c\ act}$). First, a change in crop type, variety or planting schedule alters the average areal crop factor (AAK_c) over the irrigation season converting ET_o to ET_c. Second, reducing the duration of irrigation via shorter season crops (Oad and Azim, 2002) converts ET_c to an 'adjusted crop evapotranspiration' ($ET_{c\ adj}$). Then $ET_{c\ adj}$ is then further reduced by using combined third and fourth corrections to arrive at actual crop ET ($ET_{c\ act}$). The third correction is 'field ET reduction' (FETR) using mulches, surface film, shade cloth and glasshouses (Tanny, 2013). The fourth applies a 'deficit irrigation

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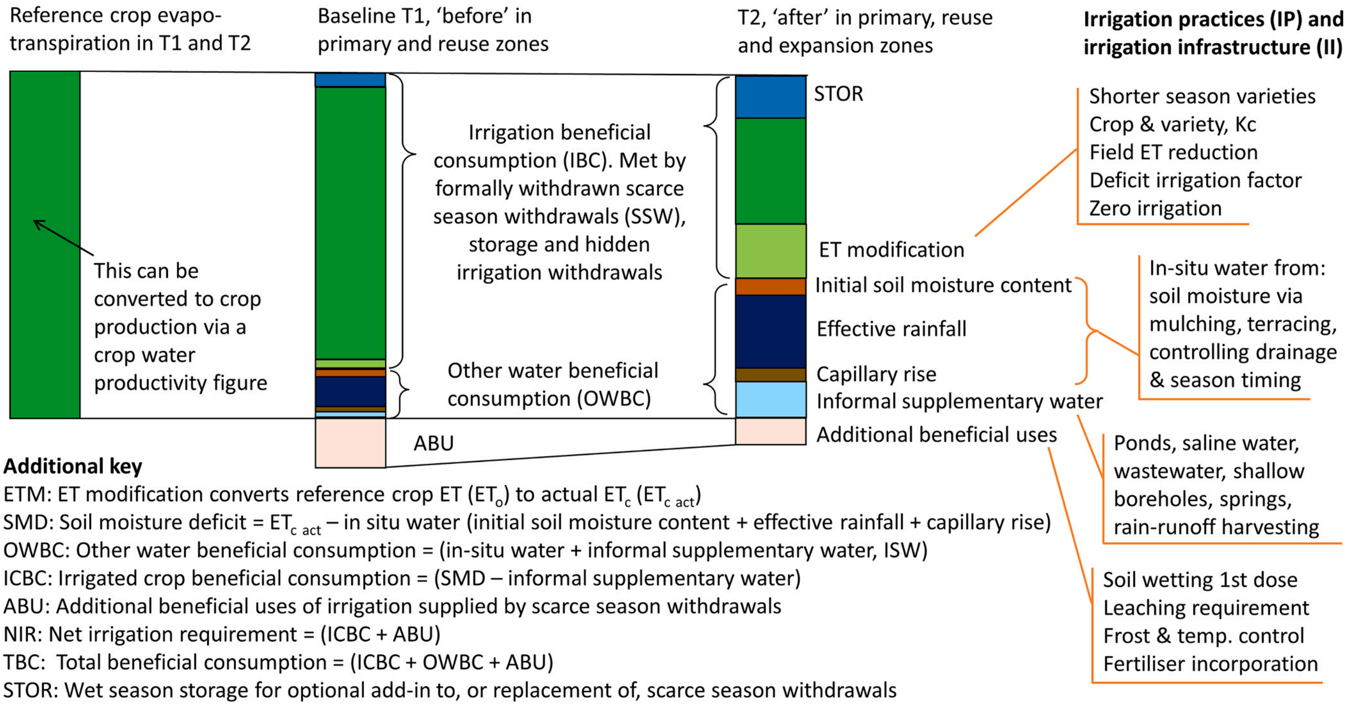
[7] The order of the ET accounting stages, addition or removal of stages, and their values are open to discussion and can be changed depending on circumstances. A future ISA might further distinguish between an 'adjusted ET_o' season length in days and an adjusted irrigating season length in days. A combined approach is currently seen in $ET_{c\ adj}$.



Additional key

ETM: ET modification converts reference crop ET (ET_o) to actual ET_c ($ET_{c\ act}$)
SMD: Soil moisture deficit = $ET_{c\ act}$ – in situ water (initial soil moisture content + effective rainfall + capillary rise)
OWBC: Other water beneficial consumption = (in-situ water + informal supplementary water, ISW)
ICBC: Irrigated crop beneficial consumption = (SMD – informal supplementary water)
ABU: Additional beneficial uses of irrigation supplied by scarce season withdrawals
NIR: Net irrigation requirement = (ICBC + ABU)
TBC: Total beneficial consumption = (ICBC + OWBC + ABU)
STOR: Wet season storage for optional add-in to, or replacement of, scarce season withdrawals
TWW: Total withdrawn water is sum of scarce season withdrawals and wet season storage
Note: The net irrigated area and length of season in days converts depth equivalents (mm) to volumes (m^3 or hm^3 = MCM)

Fig. 2. ISA soil-crop evapotranspiration accounting.

factor' (DIF) (Saitta et al., 2021). A potential fifth correction exists; under severe drought, ET is reduced further by ceasing irrigation in selected fields (Lankford et al., 2023). However, in ISA, a cessation of irrigation is shown in a lower DIF. Via these means, ET is managed by farmers across their whole farm area, rather than defined solely by agrometeorology. The difference between ET_0 and $ET_{c\ act}$ is a depth equivalent or volume of water termed 'ET modification' (ETM). ETM is managed prudently to ensure it does not impact crop production.

2) Once $ET_{c\ act}$ is derived, ISA can meet this met by managing in-situ soil water including; initial soil moisture content (ISMC)[8]; effective rainfall and dew (Pe); and capillary rise (Cg, which includes water moving laterally from higher up). Thus, the soil moisture deficit (SMD) after being met by in-situ water can be calculated; SMD = $ET_{c\ act}$ – (ISMC + Pe + Cg).
3) The SMD can be met from informal supplementary water (ISW). ISW sources are informal and located within the irrigation system or farm. Examples include rainwater harvesting into fields, farm ponds, small springs, and local boreholes. ISW cannot be easily regulated or reallocated to others. ISA terms $ET_{c\ act}$ met by in-situ water and ISW 'other water beneficial consumption' (OWBC). Thus OWBC = (ISMC + Pe + Cg + ISW).
4) Actual crop ET not met from in-situ and informal supplementary water must be replaced by irrigation. The $ET_{c\ act}$ met by irrigation water is termed 'irrigated crop beneficial consumption', where ICBC = (SMD – ISW).
5) ISA can add in and account for the management of 'additional beneficial uses' (ABU) (Jensen, 1983) such as water to leach out salts from the soil profile, or for frost and temperature control. Thus, ISA computes the total net irrigation need (NIR) as the sum of ICBC and ABU (Brouwer et al., 1992; Pereira et al., 2021a). Note also; ISA sums total beneficial consumption, TBC = (ICBC + OWBC + ABU), which is equivalent to $ET_{c\ act}$ + ABU.
6) NIR is then met from formally withdrawn water termed 'scarce season withdrawal' (SSW), This water is scarce-season and formal, meaning it is legal, regulated, bulk, measurable and reallocatable to other users and it comes from catchment-significant sources such as streams and rivers.
7) SSW can be augmented by two means – the first being hidden withdrawals. This is achieved in ISA by manually increasing SSW (see Case 10 in Section 3.3.4). Second, water from large-scale storage can be added to SSW (see Section 2.2.6).

2.2.5. *Irrigation efficiency hydrology and ratios*

Seen as a flowchart (Fig. 3), ISA accounts for irrigation efficiency via four ratios that determine the dispositions of withdrawn water flowing through the primary zone. As manual inputs to the model, these are the; classical irrigation efficiency (CIE%); recovered fraction ratio (RFR%); non-beneficial ratio (NBR%); and the reused recovered ratio (RRR%). A (fifth) CIE ratio separately applies to irrigation in the reuse zone. (Table 4 below shows the ratios selected for 14 cases).

CIE is central to the hydrology of the primary zone as it defines the; 1) gross irrigation requirement (GIR, from the net irrigation requirement, NIR) which in turn determines the required irrigation withdrawals; and 2) primary zone all losses (PZAL) where PZAL is the difference between GIR and NIR. Thus, the PZ CIE becomes an actuator affecting the changing hydrology and areas of the three irrigation zones connected to water dispositions in T1 and, when CIE is changed in T2, over time.

The recovered fraction ratio (RFR%) divides the PZAL into the recovered fraction (RF) and primary zone depleted losses (PZDL). The non-beneficial ratio (NBR%) apportions the PZDL into NBC and the NRF,

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[8] Initial soil moisture is separated out from rainfall capture because farmers can bolster soil moisture at the start of the season such as moving the time of planting. ISA uses zero or minimal amounts to demonstrate its purpose.

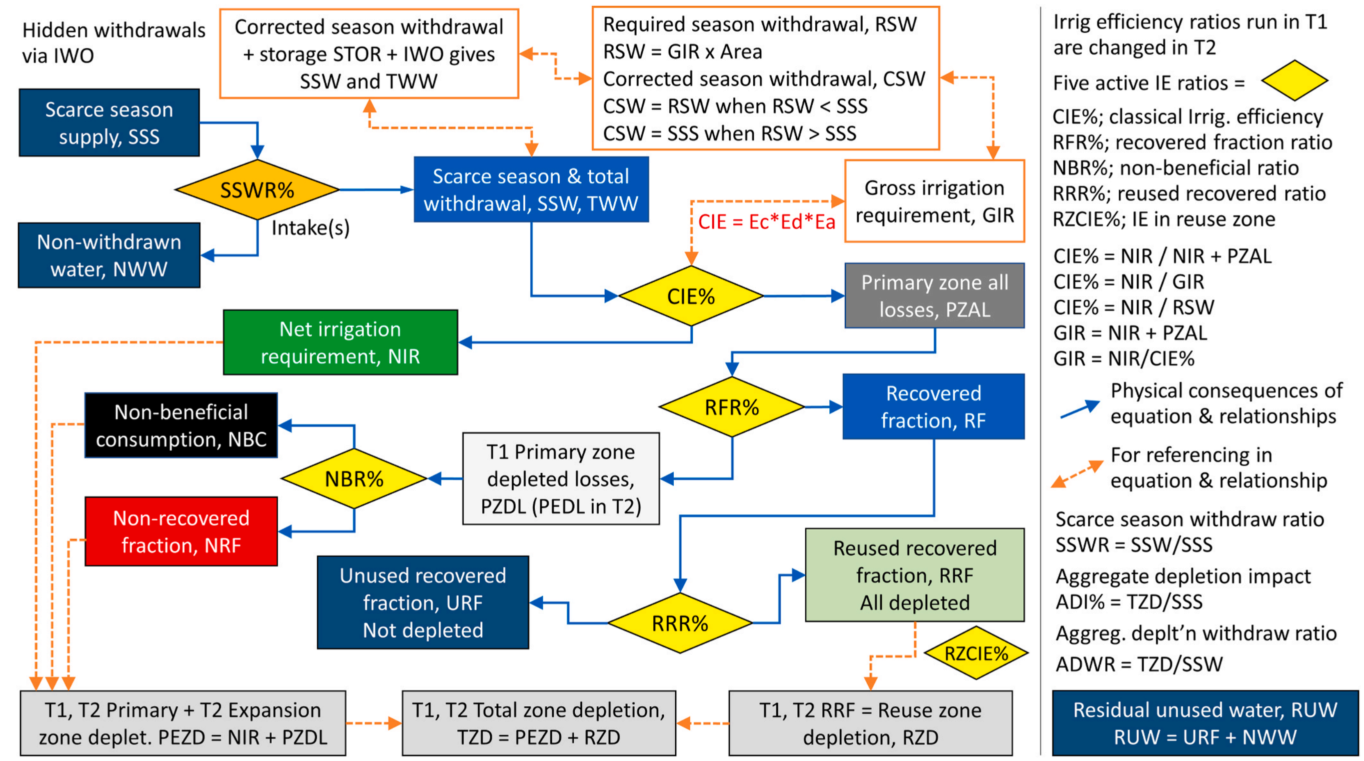

Fig. 3. The irrigation efficiency agro-hydrology of ISA.

both of which are no longer available for productive use. The reused recovered ratio (RRR%) splits the recovered fraction (RF) into a reused recovered fraction (RRF) and an unused recovered fraction (URF). The RRF is depleted in the reuse zone, and URF is not depleted (and is available for users downstream). The model assumes all water in the reuse zone is depleted with no further recovered flows.

Accompanying the four main ratios, ISA incorporates three system-level efficiencies; conveyance efficiency (Ec), distribution efficiency (Ed) and field efficiency (Ea). Two, Ec and Ed, are manually entered into the Excel model, giving a computed field efficiency where Ea = CIE/(Ec*Ed) (Jensen, 1983). Ea then allows ISA to compute the difference between withdrawal volumes and field-applied volumes (see Section 4.1.4 and Appendix A).

Fig. 3 shows three other calculated ratios that provide useful information. The scarce season withdrawal ratio (SSWR) indicates how much of the catchment's scarce season supply is withdrawn by irrigation (SSWR = SSW/SSS). The aggregate depletion impact (ADI) calculates the impact of total zone depletion on the catchment's water supply (ADI = TZD/SSS). The aggregate depletion withdraw ratio (ADWR) records the proportion of withdrawn water that is depleted (ADWR = TZD/SSW).

2.2.6. *Catchment seasonality, supply and seasonal storage*

ISA is season-aware; it focusses on the management of water in scarce (non-peak) periods and seasons. This selectivity arises because during the wet season, excess rainfall and high river flows can; a) nullify irrigation demand; b) create an 'in surplus' catchment that meets all-sector demands; and c) refill water bodies such as dams and groundwater ready for draw-down during the next water-scarce season. Differentiating between seasons allows depletion-based allocation to be managed by altering withdrawal rates and timing in relation to the regime of scarce water supplies in the catchment (Thapa and Scott, 2019) and, if relevant, by carrying water over from wet season storage (McCartney and Smakhtin, 2010). Case 11 below and Appendix A provide further information on seasonality and use of storage.

2.2.7. *Basin supply withdrawal rules*

ISA starts its water accounting with the scarce season supply (SSS) and then uses a set of rules and computations to determine the all-important 'scarce season withdrawal' (SSW) diverted from SSS. In WA it is not clear what rules, if any, determine supply and withdrawals. Appendix A explains the rules in detail (see also Fig. 4). Using these rules, ISA derives 10 types of intermediate and final water volumes which change over time from T1 to T2. These are; 1) the scarce season supply (SSS); 2) the baseline season withdrawal (BSW); 3) the new T2 required season withdrawal, (RSW); 4) a corrected withdrawal (CSW) when RSW exceeds the basin supply or intake capacity; 5) an automatic calculation or manual adjustment of the T2 irrigation withdrawal overplus (IWO, including for hidden withdrawals); 6) the calculation of the irrigation withdrawal shortfall (IWS) if this arises; 7) an entry for seasonal storage (STOR); 8) by correcting for storage, a calculation of the scarce season withdrawal (SSW); 9) the total withdrawn water (TWW); and 10) the non-withdrawn volume (NWW).

2.2.8. *Irrigated system accounting of multiple fractions and flows*

To arrive at a comprehensive model of aggregate depletion in an irrigated catchment, the volumes of many fractions/flows and dispositions must be accounted for (Fig. 4). These can be divided into five groups; T1 primary zone withdrawal dispositions, other T1 and T2 zone dispositions, other salient flows, composite flows, and system losses.

- In the first group, ISA accounts for six dispositions of the withdrawn water taken into the primary zone in T1. These are the; 1) irrigated crop beneficial consumption (ICBC); 2) additional beneficial uses (ABU); 3) non-beneficial consumption (NBC); 4) non-recovered fraction (NRF); 5) reused recovered fraction (RRF, giving rise to

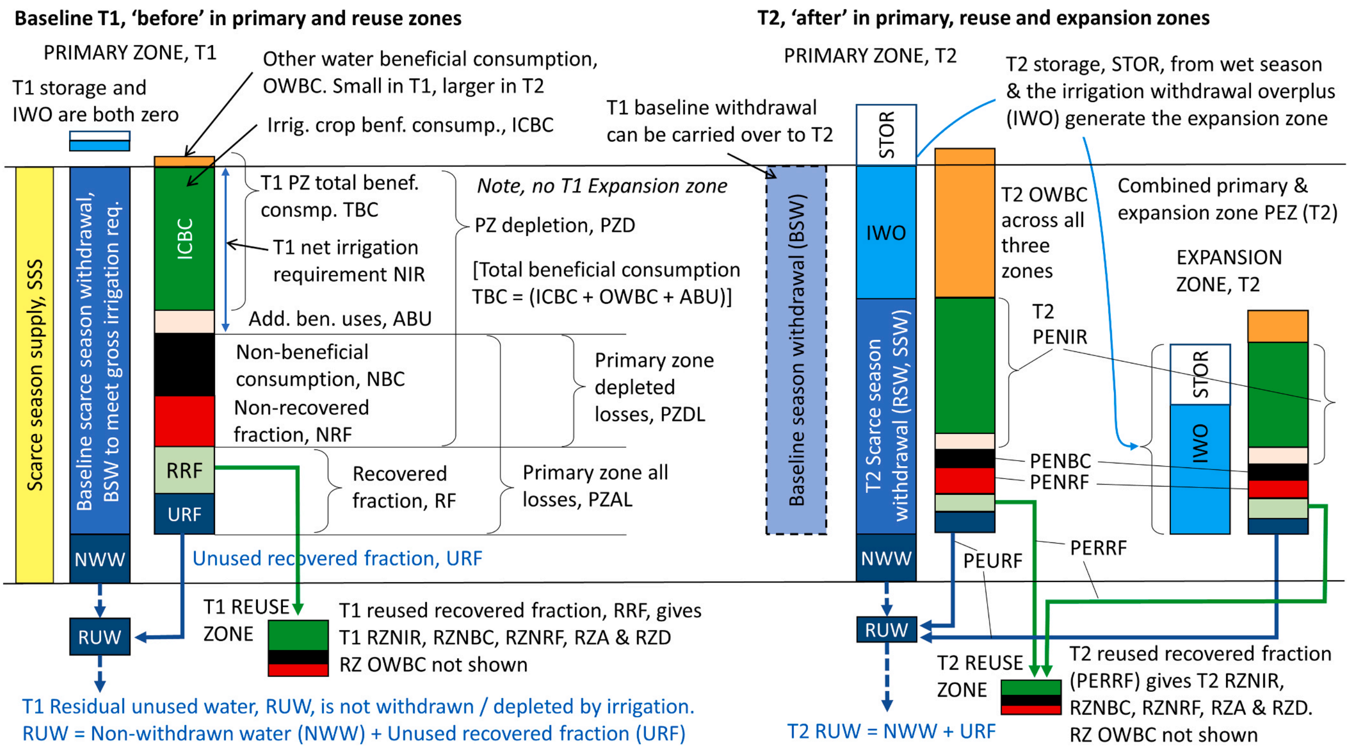

Fig. 4. Supplies, withdrawals and dispositions in ISA.

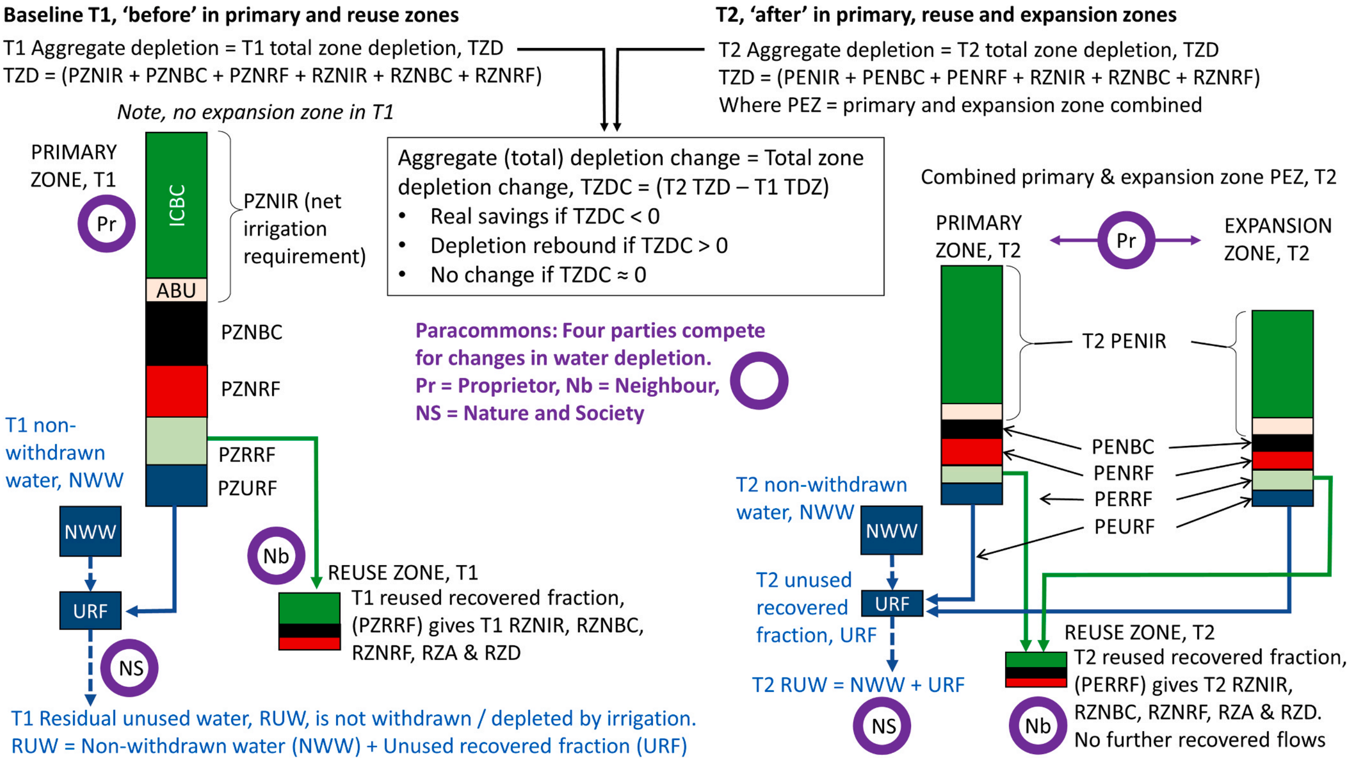

Fig. 5. Changes in total depletion and its redistribution.

the reuse zone); and 6) unused recovered fraction (URF). The prefix PZ associates these with the primary zone.

- Other T1 and T2 dispositions cover the: 1) dispositions from what becomes the combined primary and expanded zone in T2 (PENIR, PENBC, PENRF, PERRF, PEURF); and 2) the T1 and T2 dispositions of water from the reuse zone (RZNIR, RZNBC, RZNRF).
- Six other salient fractions/flows are the; 1) the scarce season supply (SSS); 2) scarce season withdrawal; 3) non-withdrawn water (NWW); 4) irrigation withdrawal overplus (IWO); 5) storage (STOR); and 6) other water beneficial consumption (OWBC) of water by crops not met by formal scarce season withdrawals. Except for IWO and STOR,[9] they occur in both T1 and T2.
- Six composite fractions/flows include the; 1) primary zone all losses (PZAL = NBC + NRF + RRF + URF); 2) primary zone depleted losses (PZDL = NBC + NRF); 3) recovered fraction (RF = RRF + URF) 4) residual unused water (RUW = NWW + URF); 5) net irrigation requirement (NIR = ICBC + ABU); and 6) total beneficial consumption (TBC = ICBC + OWBC + ABU). These also have their T1 and T2 forms, and are coded and calculated per zone.
- Three types of system-level losses (not shown in Fig. 4) comprise the; 1) conveyance losses (Ec); 2) distribution losses (Ed); and 3) field application losses (Ea). Volumes are derived for each zone from the application of the relevant efficiency ratios outlined in Section 2.2.5. Relevant zonal prefixes give; 'PEZEa, PEZEd, PEZEc' for the combined primary and expanded zone; 'PZEa, PZEd and PZEc' for the primary zone, pro rata calculated; and 'EZEa, EZEd and EZEc' for the expansion zone, pro rata calculated. In the current version of ISA, system-level losses are not calculated for the reuse zone.

2.2.9. Changes in total zone (aggregate) depletion and area

ISA is able to show how reductions in aggregate depletion (real savings), or no change in depletion, or rebounds in depletion arise. To better illustrate changes in aggregate depletion, Fig. 5 removes from Fig. 4 the water supplies, storage, withdrawals and other water beneficial consumption leaving behind only the SSW withdrawal dispositions and the non-withdrawn water. In both T1 and T2, aggregate water depletion is the sum of five fractions: 1) irrigated crop beneficial consumption (ICBC); 2) additional beneficial uses (ABU); 3) non-beneficial consumption (NBC); 4) non-recovered fraction (NRF); and 5) reused recovered fraction (RRF). (Recall, net irrigation requirement is the sum of ICBC and ABU). As shown in Fig. 5. these fractions are zone-specific, comprising the primary zone (PZ) in T1, the combined 'primary plus expansion zone' (PEZ) in T2, and the reuse zone (RZ) in both T1 and T2. (Note, total zone depletion (TZD) is equal to aggregate depletion).

By calculating per-zone depletions over time, ISA quantifies changes in total zone water depletion. These changes over time are expressed as reductions (negative change or real savings), neutral (no change) or increases (positive change or rebound). In other words, a real saving is where T2 aggregate depletion is less than T1 total depletion, and a rebound is where T2 depletion is greater than T1 depletion. Combining the unused recovered flows (URF) and non-withdrawn water (NWW) gives the residual unused water (RUW). Except during drought, a reduction in total zone depletion over time is signalled by a concomitant increase in RUW which can be reallocated. Alongside the computation of per-zone depletion, ISA calculates per-zone and total zone areas in hectares. This allows ISA to demonstrate area and depletion can change separately.

2.2.10. Water reallocation accounting

After deducing T1 to T2 changes in per-zone and total depletion, ISA determines who gains and loses water volumes across the irrigated basin. To analyse these winners and losers, ISA employs the paracommons concept (Lankford, 2013; Lankford and Scott, forthcoming) which considers that four parties vie for water gains. These four parties known as paracommoners (seen in Fig. 5). They are; the 'proprietor' (defined by 'the primary and expanded' zone); an 'immediate neighbour' (defined by the reuse zone); and combined 'nature and society' (given by the water not withdrawn and not depleted by irrigation). This analysis is provided in Appendices A and B.

2.2.11. Pareto checks of depletion and crop production

ISA can derive reallocatable reductions in total depletion that do not harm crop production. Because crop evapotranspiration is a proxy of crop production (Pérez-Blanco et al., 2020), ISA can conduct pareto checks on the change in the depletion of water compared to the change in crop production. This means appropriate IE+IP+II selections can deliver pareto-efficient reductions in depletion. However, the validity of this depends on managing soil moisture and crop evapotranspiration in ways that do not harm crop production (Cai et al., 2023). This task acknowledges the thorny question of whether any reduction of crop ET, no matter how small, impacts negatively on crop yield. For example on page 220 Pérez-Blanco et al. (2020) assert that yield is a near-linear function of crop water transpiration. Setting aside the spread of the yield/ET data they are drawing on and an interpretation of what "near linear" means, it is possible to argue there are circumstances whereby ET can be modified downwards without reducing yield (Wellington et al., 2023) given the following:

- More efficient management of irrigation benefits crop productivity (see Section 4.1.9). Higher IE brings better-timed irrigation scheduling (Lankford, 2012); makes irrigation scheduling more predictable allowing farmers to co-ordinate other inputs; and spreads water more uniformly through and between fields and farms which benefits the use of other inputs.
- Farming with irrigation is a 'system' meaning that, within certain limits, farmers respond to water scarcity by controlling other resources and problems; fertiliser applications can be more carefully placed and dosed, or pests and diseases more determinedly tackled. Thus, crop productivity can be improved to compensate for smaller water applications (Cai et al., 2023).
- Farmers are pushed by climate change and water scarcity to seek varieties with an improved water use efficiency (WUE) where progress in crop breeding for WUE has occurred (Hatfield and Dold, 2019; Morison et al., 2008). This is particularly the case where yield and WUE can be boosted when shorter-season varieties are selected (Howell et al., 1998). On this basis, ISA applies a 5 % uplift to WUE in Cases R3 and R6 (below) where a shorter-season crop is applied.
- Water reallocation in closed river basins might consider the Kaldor–Hicks test to guide 'allocation pragmatism'. Closed basins can no longer can defend the purity of not risking any cut in production if; a) farmers can compensate for yields and incomes in other ways; and b) reallocating water boosts basin economies more than crop impacts experienced (Prieto, 2021).

To derive crop yield in tonnes for each scenario, ISA first selects a value for crop water productivity (CWP, also referred to as water use efficiency) in tonnes crop per hectometre evapotranspired. In ISA's test cases, this is set at 2500 t/hm^3 for maize (Hatfield and Dold, 2019). ISA then multiplies CWP by the total zone adjusted crop evapotranspiration ($ET_{c\ adj}$) volume (hm^3). This is the ET_c which is corrected for the duration of its irrigated growing period. As mentioned above, a percentage uplift can be applied to the CWP to compensate for biologically efficient short-season varieties.

By selecting the higher-volume adjusted crop ET ($ET_{c\ adj}$) rather than the lower-volume actual crop ET ($ET_{c\ act}$), crop production is kept higher for the water savings intended by dropping the ET_o to the actual crop ET. However, when deriving the lower $ET_{c\ act}$, ISA deploys prudent changes (5–10%) to the other three ETM stages (average areal crop factor, field

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[9] The T1 STOR is set at zero for this paper. Real-world cases might apply other values.

Table 2
ISA's 20 Cases of IE, II and IP changes to ago-hydrology.

CASE # AND NAME	BRIEF DESCRIPTION AND OUTCOMES
No change over time	
1. Baseline T1 and reuse paradox	Baseline with CIE = 45% against which most cases are compared (not #3 or #12). In #1, reuse of water increases area & depletion over space, not over time
Cases 2–6. The main IE paradoxes; depletion and area change over time	
2. Paper vs real savings	CIE 85 %, no IWO; different changes to withdrawals and depletion over time
3Base. Full reuse paradox	CIE 45 %, baseline case for 3A and 3B where losses are 100 % recovered
3A. Full reuse paradox	CIE 85 %, with IWO; losses are 100 % recovered, no change in depletion
3B. Full reuse paradox	CIE 85 %, no IWO, losses are 100 % recovered but depletion reduces
4. Depletion & area rebound	CIE 85 %, with IWO; depletion and area increase
5. Crop ET rebound	CIE 85 %, with IWO; depletion increases, area neutral
6. Duration rebound	CIE 85 %, same SSW as Case 1; depletion increases, area down
Cases 7–11. Area rebounds from IP+II factors but not necessarily an increase in depletion	
7. Soil-crop-ET	CIE 45 %, crop factors; shading; deficit irrig; leaching req't
8. Duration of irrigation	CIE 45 %, shorter season crop; shorter stages, withheld stages
9. Wetted area control	CIE 45 %, partial root wetting; area control; field margins, fallow/zero irrigation
10A. In-situ soil moisture mgt	CIE 45 %, rainfall/dew; initial soil moisture; capillary rise
10B. Informal water	CIE 45 %, local water; farm ponds; local boreholes; springs; waste/saline water
10C. Hidden water	CIE 45 %, hidden withdrawals added to formal withdrawals
11A. Storage mitigates drought	CIE 45 %, with drought, stored water supplements SSW; SSW depletion neutral
11B. Storage adds to SSW	CIE 45 %, stored water supplements SSW (no drought); SSW depletion neutral
11C. Storage replaces SSW	CIE 45 %, stored water replaces SSW (no drought); SSW depletion decreases
Case R1 to R6. Pareto-checked depletion-based water allocation applying higher IE in 'B'	
R1A&B. Primary/total Z area	CIE A = 45 %, B = 85 %, primary zone & total zone areas cut
R2A&B. Withdrawals cut	CIE A = 45 %, B = 85 %, withdrawals are cut
R3A&B. Irrigation duration	CIE A = 45 %, B = 85 %, time duration of irrigating is reduced
R4A&B. Seasonal storage	CIE A = 45 %, B = 85 %, large-scale season storage is applied
R5A&B. Controlling reuse	CIE A = 45 %, B = 85 %, no reuse of recovered flows is allowed
R6A&B. All combined	CIE A = 45 %, B = 85 %, eleven IP and II variables are deployed
Cases 12–14. Pitfalls that produce other outcomes	
12Base. Low return flows pitfall	CIE 45 %, baseline case for 12A and 12B with only 10 % recovered flows
12A. Low return flows pitfall I	CIE 85 %, with IWO, no recovered losses; area up but depletion neutral
12B. Low return flows pitfall II	CIE 85 %, no IWO, no recovered losses; small cut in area and depletion down
13. Inefficient systems throttled	CIE 10 %, withdrawals for inefficient systems exceed supply; area down but depletion up
14. Area/depletion uncorrelated	CIE 45 %, irrigated area up, depletion down; due to soil-crop water management

Abbreviations are defined in Table 1.

ET modification and deficit irrigation). Crop production is not greatly diminished in this range provided irrigation and rainfall is adequate and timely (Basso, Ritchie, 2018), and coincide with less water-sensitive periods of crop development (Robertson et al., 1999). ISA also; a) minimally alters the average areal crop factor (AAK_c) to reflect cropping pattern changes with the same crop rather than changing to a different crop type (Mbava et al., 2020); and b) does not apply a cessation of irrigation. These two steps would complicate the pareto validation.

2.2.12. Other ISA metrics

ISA derives other performance metrics such as; the effective irrigation efficiency (EIE%) across the whole irrigated zone; the area irrigated per cubic hectometres (hm^3) withdrawn; and the area irrigated per hm^3 depleted. These metrics are briefly described in Appendix A.

2.3. Excel spreadsheet model

Drawing on the above, an Excel spreadsheet (Appendix B) compares different cases of depletion-based water saving. This model comprises 15 stages of calculations containing spreadsheet rows of input variables and formulae, and columns of different cases. Stage 1 sets the irrigation and soil-crop evapotranspiration variables. Stage 2 contains the irrigation efficiency computations. Stage 3 calculates withdrawals. Stages 4–8 determine per-zone outcomes. Stages 9–15 generate aggregate outcomes, paracommons water distribution, and other metrics. Appendix A describes these stages in detail.

2.4. Future versions of ISA

Future versions could add further variables and steps to the model, as well as address other functions of water accounting (see Appendix A). These might; 1) compare differences between intake withdrawals and field applications of water; 2) assess the 'costs' of water management, for example, seen in the timing and equity of water distribution; 3) manage irrigation resilience during drought (Lankford et al., 2023); 4) daily manage irrigated systems; 5) study performance (i.e. productivity and farmer economic profit); 6) build related metrics such as water-energy-food trade-offs (i.e. energy for aquifer pumping); and 7) model the effects of allocation on economic productivity.

2.5. Applying ISA to examine cases of water conservation

The paper employs 20 cases (Table 2**)** to examine water conservation outcomes including six pareto-checked depletion-based reallocation cases. By comparing them to the T1 Baseline Case, these cases produce changes in area, depletion and other outcomes. Cases 3 and 12 have their own baseline. Baselines need not be the original irrigation system, but a moment in time existing prior to later change. In the order of presentation in the paper, the 20 cases are as follows:

- Case 1 presents the 'reuse paradox' when a primary zone produces return flows that are reused 'within time' to create greater depletion and area than explained by the primary zone alone.
- Case 2 reproduces the 'paper vs real savings' paradox. Raising CIE over time results in smaller paper savings (cuts to applications and withdrawals) than real savings (cuts to depletion).
- Case 3 presents two '100% recovery' versions of the paper vs real savings paradox.
- Cases 4–6 present three depletion rebound paradoxes caused by a higher IE.

Table 3
Main input variables Cases 1–14.

Case and number	PZA ha	ETo mm	AAKc	ETc mm	ITD Days	ETc adj mm	FETR	DIF	ETc act mm	ISMC mm	Pe mm	Cg mm	SMD mm	ISW mm	OWBC mm	ICBC mm	ABU mm	NIR mm	TBC mm	IAC	NIA ha
1. Baseline	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
2. Paper vs real savings	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
3Base. Full reuse paradox	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
3A. Full reuse paradox	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
3B. Full reuse paradox	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
4. Depletion & area rebound	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
5. Crop ET rebound	400	640	1.06	679	140	679	1.00	1.00	679	0	110	0	569	0	110	569	70	639	749	1.00	400
6. Duration rebound	400	640	0.80	512	254	929	1.00	1.00	929	0	110	0	819	0	110	819	70	889	999	1.00	400
7. Soil-crop-ET	400	640	0.75	480	140	480	0.95	0.95	433	0	110	0	323	0	110	323	50	373	483	1.00	400
8. Duration of irrigation	400	640	0.80	512	126	461	1.00	1.00	461	0	110	0	351	0	110	351	70	421	531	1.00	400
9. Wetted area control	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	0.95	380
10A. In-situ soil moisture mgt	400	640	0.80	512	140	512	1.00	1.00	512	30	125	10	347	0	165	347	70	417	582	1.00	400
10B. Informal water	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	50	160	352	70	422	582	1.00	400
10C. Hidden water	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
11A. Storage mitigates drought	401	640	0.80	512	140	512	1.00	1.00	512	0	0	0	512	0	0	512	70	582	582	1.00	401
11B. Storage adds to SSW	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
11C. Storage replaces SSW	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
12Base. Low return flows	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
12A. Low return flow pitfall I	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
12B. Low return flow pitfall II	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
13. Inefficient systems shrink	400	640	0.80	512	140	512	1.00	1.00	512	0	110	0	402	0	110	402	70	472	582	1.00	400
14. Area/depltn uncorrelated	400	640	0.75	480	126	432	0.95	0.95	390	30	125	10	225	50	215	175	50	225	440	0.95	380

Abbreviations are defined in Table 1.

- Cases 7–11 reveal how changes to irrigation practices (IP) and irrigation infrastructure (II), not irrigation efficiency, raise irrigated areas but not necessarily depletion.
- R1 to R6 present six cases of pareto-checked depletion-based water conservation for reallocation.
- Cases 12–14 act as pitfalls when discussing irrigation water conservation.

3. Results

3.1. Introduction and baseline case 1

Tables 3–5 present summary information of Cases 1–14. Detailed and quantitative descriptions of all the cases, including accompanying diagrams and further results, are presented in Appendices A and B. The Baseline Case 1 irrigation system of 400 ha experiences 640 mm seasonal reference crop evapotranspiration and 110 mm effective rainfall. It is in a catchment with a scarce season supply of 5.32 hm^3; it withdraws 4.20 hm^3 and depletes a total of 3.85 hm^3. Case 1 is irrigated for 140 days with an average areal crop factor of 0.80, an irrigation efficiency of 45 %, a 60 % recovered fraction ratio (RFR), of which 75 % is reused (RRR), and a non-beneficial ratio (NBR) of 80 %. These values for RFR %, NBR% and RRR% are maintained for all cases (except for Cases 3, 12, 13 and R5) leading to fractions falling within the ranges given by Grafton et al. (2018).

3.2. Six mainstream irrigation efficiency paradoxes

ISA demonstrates the six irrigation efficiency paradoxes found in the literature. The paradoxes are presented independently but they can overlap and be confused for each other. Furthermore, depending on prevailing consensus, one's irrigation knowledge, or reaction to the number of permutations, it is possible to consider all 20 cases in the paper are paradoxes. Graphs of the six cases are given in Appendix A.

3.2.1. Case 1; cross-scale reused recovered flows

Case 1 is the cross-scale 'reuse' paradox. It could be considered as the original IE paradox which other IE paradoxes stem from or relate to as they grapple, correctly or mistakenly, with the fates of recovered water. This paradox describes situations when losses from an irrigation system pass to an aquifer or drainage system and are reused locally or elsewhere in the basin (left side of Fig. 6). When reuse is by irrigation, it gives rise to a larger total irrigation area and depleted volume than is occurring in the primary irrigation zone alone. This reuse paradox arises because the CIE of the primary zone fails to capture the fate of recovered losses (Willardson et al., 1994).

Via reuse of water, Case 1 witnesses an extra 198 ha irrigated in the reuse zone, above the 400 ha of the primary zone, bringing the total zone area to 598 ha. Furthermore, total zone depletion is 3.85 hm^3, higher than the primary zone's depletion of 2.81 hm^3. It is important to reiterate that a) reuse of losses occurs within time, meaning it is nearly contemporaneous as the withdrawal of water into the primary zone; and b) no increase in irrigation efficiency occurred over time and no increase in area occurred over time. The extra area and depletion from reuse are not rebounds over time.

3.2.2. Case 2; real vs paper savings paradox

Case 2′s paradox adds an 'over time' improvement to the irrigation efficiency alongside recovery of losses seen in Case 1. In debates about 'raising irrigation efficiency to save water', attention is correctly drawn to 'paper water savings' (dry savings) against 'real water savings' (wet savings) (Keller et al., 1996; Seckler, 1996). The difference between these two types of savings depends on the fates of losses observed in Case 1; whether water lost from one scale (the field) are recovered by the farm, irrigation system or river basin, and whether this recovery is recognised when managing savings. 'Real water savings' is about

Table 4
Efficiency hydrology ratios Cases 1–14.

Case # and name	PZCIE %	Ec %	Ed %	Ea %	GIR mm	RFR %	NBR %	RRR %	RZCIE %
1. Baseline	45%	80%	80%	70%	1049	60%	80%	75%	90%
2. Paper vs real savings	85%	95%	95%	95%	555	60%	80%	75%	90%
3Base. Full reuse paradox	45%	80%	80%	70%	1049	100%	80%	100%	90%
3A. Full reuse paradox	85%	95%	95%	95%	555	100%	80%	100%	90%
3B. Full reuse paradox	85%	95%	95%	95%	555	100%	80%	100%	90%
4. Depletion & area rebound	85%	95%	95%	95%	555	60%	80%	75%	90%
5. Crop ET rebound	85%	95%	95%	95%	752	60%	80%	75%	90%
6. Duration rebound	85%	95%	95%	95%	1046	60%	80%	75%	90%
7. Soil-crop-ET	45%	80%	80%	70%	829	60%	80%	75%	90%
8. Duration of irrigation	45%	80%	80%	70%	935	60%	80%	75%	90%
9. Wetted area control	45%	80%	80%	70%	1049	60%	80%	75%	90%
10A. In-situ soil moisture mgt	45%	80%	80%	70%	927	60%	80%	75%	90%
10B. Informal water	45%	80%	80%	70%	938	60%	80%	75%	90%
10C. Hidden water	45%	80%	80%	70%	1049	60%	80%	75%	90%
11A. Storage mitigates drought	45%	80%	80%	70%	1293	60%	80%	75%	90%
11B. Storage adds to SSW	45%	80%	80%	70%	1049	60%	80%	75%	90%
11C. Storage replaces SSW	45%	80%	80%	70%	1049	60%	80%	75%	90%
12Base. Low return flows	45%	80%	80%	70%	1049	10%	50%	75%	90%
12A. Low return flows pitfall I	85%	95%	95%	95%	555	10%	50%	75%	90%
12B. Low return flows pitfall II	85%	95%	95%	95%	555	10%	50%	75%	90%
13. Inefficient systems shrink	10%	50%	50%	40%	4720	60%	80%	75%	90%
14. Area/depltn uncorrelated	45%	80%	80%	70%	500	60%	80%	75%	90%

Abbreviations are defined in Table 1.

recognising this recovery to account for depleted water from the perspective of the scale that includes the recovered fraction being reused, normally the river basin.

The notion of paper water savings, on the other hand, takes the perspective of reducing withdrawals into a unit at a given scale-level (e.g. field, farm or system), whilst recognising (or failing to recognise) these withdrawals contain in them water losses recovered to the basin. Thus efficiency-driven reductions of the water withdrawn into an irrigation system (paradoxically so the argument goes) do not increase the amount of water in the basin. This is because if irrigation losses are recovered to the basin (i.e. not depleted by the irrigation system), then reducing these types of recovered losses makes no difference to the amount of water in the basin. It is this recovery of losses which means, that despite their reduction (as a part of reducing withdrawals), real water savings have not occurred.

Although these losses and their reuse occur within time as described in Case 1, Case 2′s paradox is 'over-time' because IE improvements to save water require time to transpire (e.g. installing new irrigation equipment) which prefigure future outcomes.[10] In the model, the Case 1 Baseline with its CIE of 45 % raises its efficiency to become Case 2′s 85 %. This higher CIE % reduces the gross irrigation requirement, which drops withdrawals going into the primary zone by nearly half and so Case 2 experiences paper savings of 47 %. The paradox is that real savings in the primary zone are only 28 % because primary zone depletion went from 2.81 hm^3 (Baseline) to 2.02 hm^3 in Case 2. While Case 2′s 'real savings are less than paper savings' agrees with the literature, these observations apply to the primary zone only. If we consider the depletion of water across the total zone, aggregate depletion (real savings) is reduced by -44 %, nearly the same as the paper savings. This counter-paradox puts a spotlight on the need to distinguish between per-zone and total zone outcomes, and leads to pitfalls covered in Section 4.

3.2.3. Case 3; full recovery no change in depletion paradox

Case 3Base, 3A and 3B explore a pure version of Case 2. With 100 % losses fully recovered, Case 3 demonstrates raising IE has no effect on saving water defined by depletion (Grafton et al., 2018). To show this, Cases 3A and 3B are compared to their own baseline '3Base', and all three cases select 100 % RFR and 100 % RRR. Cases 3A and 3B both increase their efficiency from 3Base's 45 % to 85 %. Despite this increased efficiency, by continuing 3Base's withdrawal volume of 4.20 hm^3 (adding an IWO of 1.97 hm^3 over what is necessary for the more efficient system), 3A depletes the same volume of water as 3Base (TDZ = 4.20 hm^3), demonstrating the 'no change in depletion paradox'. (However, Case 3B does not apply an IWO; the cut in Case 3B's withdrawals cuts its aggregate depletion. Pitfalls with the 100 % recovery paradox, employing Case 3B, are discussed in Section 4).

3.2.4. Case 4; IE-induced depletion and area rebound

Before Case 4 is explained, it is important to say there are three depletion rebound cases; 4–6. The rebounds in these cases are not caused by the recovery of losses elsewhere in a reuse zone as in Cases 1–3. The rebounds occur because the effects of a future higher primary zone efficiency and the continuation of the Baseline's withdrawn volume play out in the primary and expansion zones. Nonetheless, recovered flows and the reuse zone are impacted. The right-hand side of Fig. 6 illustrates Cases 4–6; with more efficient irrigation, a continuation of the Baseline's withdrawal (adding an IWO) allows depletion to increase in the three ways given by Cases 4–6.

Case 4 exemplifies an IE-induced rebound in area, crop ET and total depletion, resulting in lower return flows and a smaller reuse zone. Case 4 applies a CIE% of 85% compared to Case 1′s 45%. This higher CIE drops Case 4′s required irrigation withdrawal of the primary zone. However, withdrawals continue at the same rate as Case 1 (4.20 hm^3) leading to an irrigation withdrawal overplus (IWO). This leads to an increased total zone area of 810 ha of 400 ha, 356 ha and 54 ha for the primary, expansion, and reuse zones respectively. Case 4′s depletion increases to 4.10 hm^3, higher than the Baseline of 3.85 hm^3. Beneficial crop consumption of the withdrawn water increases in both relative and absolute terms.

3.2.5. Case 5; crop ET depletion rebound, same area

Supported by a higher IE, Case 5 switches to a more water intensive crop (Grafton et al., 2018) resulting in higher crop ET but on the same irrigated area as the Baseline. Case 5 increases CIE to 85% and maintains the Baseline withdrawal at 4.20 hm^3. It employs Excel's Goal Seek to set the average areal crop factor (AAKc) at 1.06 reflecting a crop that

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[10] See also the discussion on the future prefiguration of savings in the para-commons (Lankford, 2013).

Table 5
Summary results Cases 1–14.

Case # and name	PZCIE %	TZEIE %	SSS Hm^3	IWO Hm^3	SSW Hm^3	SSWC Hm^3	SSWC %	PZA Ha	EZA Ha	RZA Ha	TZA Ha	TZAC Ha	PEZFA Hm^3	TZD Hm^3	TZDC Hm^3	TZDC %	ADI %	ADWR %
1. Baseline	45 %	73 %	5.32	0.00	4.20	0.00	0 %	400	0	198	598	0	2.69	3.85	0.00	0 %	72 %	92 %
2. Paper vs real savings	85 %	93 %	5.32	0.00	2.22	-1.97	-47 %	400	0	29	429	-169	2.00	2.17	-1.68	-44 %	41 %	98 %
3Base. Full reuse paradox	45 %	95 %	5.32	0.00	4.20	0.00	0 %	400	0	440	840	0	2.69	4.20	0.00	0 %	79 %	100 %
3A. Full reuse paradox	85 %	99 %	5.32	1.97	4.20	0.00	0 %	400	356	120	876	36	2.00	4.20	0.00	0 %	79 %	100 %
3B. Full reuse paradox	85 %	99 %	5.32	0.00	2.22	-1.97	-47 %	400	0	64	464	-376	2.00	2.22	-1.97	-47 %	42 %	100 %
4. Depletion & area rebound	85 %	93 %	5.32	1.97	4.20	0.00	0 %	400	356	54	810	212	2.00	4.10	0.25	7 %	77 %	98 %
5. Crop ET rebound	85 %	93 %	5.32	1.19	4.20	0.00	0 %	400	158	40	598	0	2.70	4.10	0.25	7 %	77 %	98 %
6. Duration rebound	85 %	93 %	5.32	0.01	4.20	0.00	0 %	400	1	29	430	-168	3.76	4.10	0.25	7 %	77 %	98 %
7. Soil-crop-ET	45 %	73 %	5.32	0.88	4.20	0.00	0 %	400	106	250	756	158	2.12	3.85	0.00	0 %	72 %	92 %
8. Duration of irrigation	45 %	73 %	5.32	0.46	4.20	0.00	0 %	400	49	222	671	73	2.39	3.85	0.00	0 %	72 %	92 %
9. Wetted area control	45 %	73 %	5.32	0.21	4.20	0.00	0 %	400	0	198	598	0	2.69	3.85	0.00	0 %	72 %	92 %
10A. In-situ soil moisture mgt	45 %	73 %	5.32	0.49	4.20	0.00	0 %	400	53	224	677	79	2.37	3.85	0.00	0 %	72 %	92 %
10B. Informal water	45 %	73 %	5.32	0.44	4.20	0.00	0 %	400	47	221	669	71	2.40	3.85	0.00	0 %	72 %	92 %
10C. Hidden water	45 %	73 %	5.32	0.20	4.40	0.20	5 %	400	19	207	627	29	2.69	4.03	0.18	5 %	76 %	92 %
11A. Storage mitigates drought	45 %	73 %	5.32	0.00	4.20	0.00	0 %	401	0	198	599	1	2.69	3.85	0.00	0 %	72 %	92 %
11B. Storage adds to SSW	45 %	73 %	5.32	0.00	4.20	0.00	0 %	400	95	245	741	143	2.69	3.85	0.00	0 %	72 %	92 %
11C. Storage replaces SSW	45 %	73 %	5.32	0.00	3.20	-1.00	-24 %	400	0	198	598	0	2.05	2.93	-0.92	-24 %	55 %	92 %
12Base. Low return flows	45 %	49 %	5.32	0.00	4.20	0.00	0 %	400	0	33	433	0	2.69	4.14	0.00	0 %	78 %	99 %
12A. Low return flows pitfall I	85 %	86 %	5.32	1.97	4.20	0.00	0 %	400	356	9	765	332	2.00	4.18	0.04	1 %	79 %	100 %
12B. Low return flows pitfall II	85 %	86 %	5.32	0.00	2.22	-1.97	-47 %	400	0	5	405	-28	2.00	2.21	-1.93	-47 %	42 %	100 %
13. Inefficient systems shrink	10 %	54 %	5.32	0.00	5.32	1.13	27 %	113	0	411	524	-74	1.33	4.60	0.75	20 %	87 %	87 %
14. Area/depltn uncorrelated	45 %	73 %	5.32	2.30	4.20	0.00	0 %	400	440	416	1255	657	1.28	3.85	0.00	0 %	72 %	92 %

Abbreviations are defined in Table 1. Total areas (TZA) are derived from TWW.

transpires more water[11] on the same total zone area as Case 1 (598 ha) but giving a higher aggregate depletion of 4.10 hm^3 (the same as Cases 4 and 6).

3.2.6. *Case 6; duration depletion rebound, smaller area*

Case 6 sees farmers use a higher IE to increase irrigation days via a longer main season or a second short irrigated season. Case 6 applies 85% CIE and uses Excel's Goal Seek to set a duration of 254 days (114 days above Baseline) to use the same withdrawal as the Baseline of 4.20 hm^3 (so no additional IWO is applied). Total zone depletion goes up from 3.85 hm^3 (Baseline) to 4.10 hm^3 in Case 6. Because greater depletion occurs in the longer-irrigated primary zone, no expansion of area takes place (EZ = 0 ha) and the reuse zone drops from 198 ha in Baseline T1 to 29 ha in T2. Note, despite its higher total depletion, Case 6‘s total zone area (430 ha) is lower than the Baseline's 598 ha.

3.3. *Five cases of irrigation practices and infrastructure*

This section discusses how irrigation practices (IP) and infrastructure (II), intending to reduce water use, paradoxically increase irrigated areas but not always water withdrawn and depleted. In the five cases (7-11), IE remains the same as the Baseline's 45%. IP and II cover; net irrigation applied; duration of irrigation; area irrigated; in-situ informal water; seasonally stored water and hidden withdrawals. Understanding these agro-hydrological factors is important otherwise increases in area could be mistakenly tied to higher IE (see discussion on area pitfalls in Section 4.1.7). Reduced-depletion versions of changes to IP and II are described by Case R6 in Section 3.4. Appendices A and B provide further information and diagrams.

3.3.1. *Case 7; area rebounds from irrigation practices*

Case 7 studies a rebound in irrigated area caused by smaller irrigation field-level applications. By changing various irrigation practices (see next paragraph), the net irrigation requirement (NIR) is reduced (from 472 mm to 373 mm). However, area increases (from 598 ha to 756 ha) because withdrawals remain the same. Total depletion remains the same as the Baseline at 3.85 hm^3. While this paradox might look familiar because of area growth, it reveals two pitfalls; a) despite the area increasing, total zone water depletion is the same, and; b) no increase in CIE was involved.

Five practices reduce NIR: 1) Growing alternative crops and varieties can see a reduction in the crop factor (Kc) leading to a drop in ET_c (Galindo et al., 2018). Although the IE paradox literature refers to a switch to more consumptive crops with a higher Kc (e.g. citrus to banana), farmers can also reverse switch in response to water shortages. 2) Using mulching, surface film, shade-cloth and greenhouses, it is possible to reduce soil evaporation and crop evapotranspiration via controlling wind, solar strength and humidity. 3) Growing crops in a wetter or cooler agroecological zones can reduce the soil moisture deficit (Lankford et al., 2023; Shrestha et al., 2021). 4) Initiating deficit irrigation (DI) scheduling to lengthen the period between irrigations or apply less water per irrigation (Saitta et al., 2021). 5) Cutting additional beneficial uses (ABU) for example by reducing the leaching requirement (LR) via improved drainage, or because LR is recalculated (Letey et al., 2011).

3.3.2. *Case 8; shorter duration of irrigation*

Case 8 explores the effect of reducing the time a farm is watered via three means. The first applies a shorter season crop and cuts the time fields are wet either at the start or end of the season (Tabbal et al., 2002). The second reduces the watering time to lower the depth of standing water in a flooded rice paddy. The third reduces the days of irrigation

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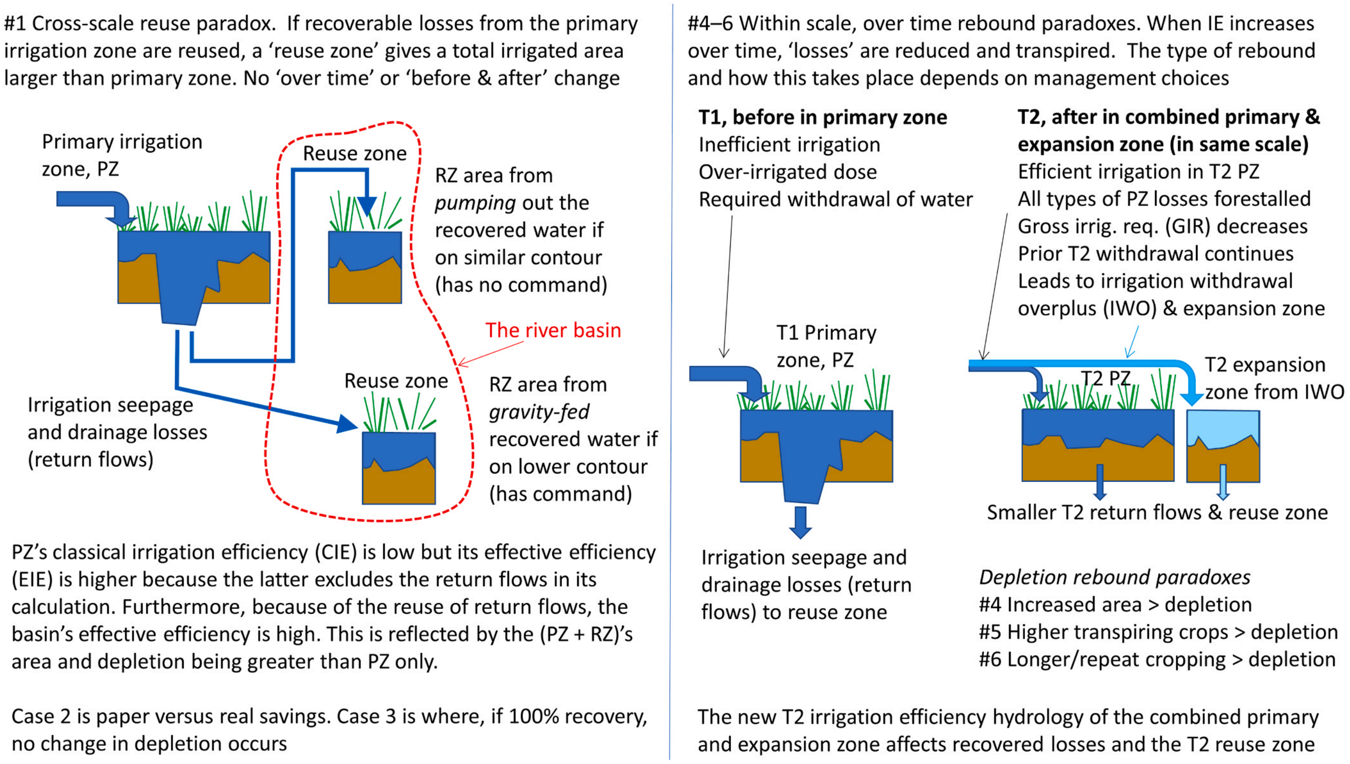
[11] A higher areal Kc can also be created via a combination of a change in crop variety and farming practices leading to crops being planted more densely or in a shorter window, meaning a less staggered pattern over time.



#1 Cross-scale reuse paradox. If recoverable losses from the primary irrigation zone are reused, a 'reuse zone' gives a total irrigated area larger than primary zone. No 'over time' or 'before & after' change

PZ's classical irrigation efficiency (CIE) is low but its effective efficiency (EIE) is higher because the latter excludes the return flows in its calculation. Furthermore, because of the reuse of return flows, the basin's effective efficiency is high. This is reflected by the (PZ + RZ)'s area and depletion being greater than PZ only.

Case 2 is paper versus real savings. Case 3 is where, if 100% recovery, no change in depletion occurs

#4–6 Within scale, over time rebound paradoxes. When IE increases over time, 'losses' are reduced and transpired. The type of rebound and how this takes place depends on management choices

T1, before in primary zone
Inefficient irrigation
Over-irrigated dose
Required withdrawal of water

T2, after in combined primary & expansion zone (in same scale)
Efficient irrigation in T2 PZ
All types of PZ losses forestalled
Gross irrig. req. (GIR) decreases
Prior T2 withdrawal continues
Leads to irrigation withdrawal overplus (IWO) & expansion zone

Depletion rebound paradoxes
#4 Increased area > depletion
#5 Higher transpiring crops > depletion
#6 Longer/repeat cropping > depletion

The new T2 irrigation efficiency hydrology of the combined primary and expansion zone affects recovered losses and the T2 reuse zone

Fig. 6. Reuse and expansion area rebound paradoxes.

within the crop season. The latter in effect ceases irrigation, and could be seen as another version of deficit irrigation, or gives rise to alternating wet and dry periods (Rejesus et al., 2011). Paradoxically, reduced time can translate to an increased area. Case 8′s time-cut of 14 days reduces the scarce-season net and gross irrigation requirement and required withdrawals. Because withdrawals continue as before via an overplus of 0.46 hm^3, the total zone area increases to 671 ha; 73 ha above Baseline. However aggregate depletion of scarce season withdrawals remains the same as the Baseline at 3.85 hm^3.

3.3.3. Case 9; irrigation area control

Case 9 observes an improved spatial control of irrigation water. This results in evaporation being reduced and either switched off (the depletion reduction version) or switched to crop ET (the depletion neutral version). Three subtypes of area control are explained in more detail in Appendix A accompanied by a diagram. They are; partial root wetting (PRW) to reduce the 'E′ part of ET relative to 'T′; tighter control of watering at the field margins where crop density may be low; and improved watering and crop uniformity by removing high and low spots in the field via machine-levelling fields or using small level plots surrounded by bunds. Case 9 applies an area correction of 0.95 to the formal primary zone of 400 ha to generate a net irrigated area (NIA) of 380 ha. This decrease does not lower the per hectare net and gross water requirement in millimetres, instead it reduces the required withdrawal volume. If Baseline withdrawals continue, a withdrawal overplus of 0.21 hm^3 occurs thereby expanding the irrigation area. In this case the 5% reduction in area gives a 5% withdrawal overplus which allows the net irrigated field area to expand back to 400 ha. This case raises possible pitfalls, discussed in Section 4.1.7.

3.3.4. Case 10; in-situ, informal and hidden water

In-situ water, covered by Case 10A, describes water added directly to or captured by the rootzone. It includes harvesting rainfall and dew (Pe), as well as managing both the initial soil moisture content (ISMC) and capillary rise from shallow water tables (Cg). Sources of 'informal supplementary water' (ISW) are described by 10B. This includes water from on-farm tanks and ponds, shallow boreholes, farm drains, local springs, saline water, and wastewater. ISW is sourced at or close to the farm or field. Case 10C describes water hidden within formal withdrawals. These sub-types of Case 10 are illustrated and described in Appendix A. Case 10 presents six considerations.

1. The CIE of the formally withdrawn water does not change. It remains at 45% for the baseline (Case 1) and 'after' Cases 10A, 10B and 10C. This creates a pitfall if rebounds in irrigated area and water depleted are mistakenly attributed to higher IE rather to increased use of in-situ, informal and hidden water.
2. Case 10A-C all witness increases in total area compared to Case 1. This occurs because, when the baseline's withdrawn water is continued, it is added to by in-situ, informal and hidden water. In the model, the irrigation withdrawal overplus (IWO) supplies the expansion zone. Aggregate depletion in 10A and 10B is the same as the Baseline, but increases in 10C.
3. ISW is physically not withdrawn through the main intake of the irrigation system; it is sourced informally and locally by farmers. This means it may not be observed, quantified or tracked by formal water flow measurement within sanctioned water withdrawals and official quotas. In other words, ISW by definition occurs outside the formal regulatory framework that might measure or physically control water quotas, licences and land use (de Fraiture et al., 2014). However, this depends on circumstances. ISA could record the use of shallow groundwater during the main irrigation season as informal and ad-hoc, but treat the abstraction of deep groundwater for full irrigation during the dry season as formal SSW withdrawals.
4. The placement and use of informal local water in the sequence of irrigation withdrawal, storage, conveyance, distribution and

application matters. If ISW replaces scarce season withdrawal, this reduces the volume of water withdrawn and subsequently depleted. Thus ISW substitution of SSW is the depletion-reduction version. If, however, informal supply is added to the same withdrawn water carried over from the Baseline, area irrigated goes up but the depleted volume of formal SSW remains the same. 'ISW addition' is the depletion-neutral version.

5. Demonstrating hidden withdrawals, Case 10C adds 0.2 hm^3 as a manual IWO entry. Hidden withdrawals can exceed calculated, licenced or physical caps. This occurs when farmers; use more of their or neighbours' licenced volumes; conjoin licences from purchased farms; fail to report under-reading intakes or canals that leak onto their farms; tamper with recording devices and gates; adjust the stage-discharge relationship at the intake; hide additional intakes, pumps and boreholes; fail to install or repair drainage overpasses allowing runoff into canals; extend hours by irrigating at night; exceed licences that are poorly specified; fail to apply drought restrictions to withdrawals; and fail to cut withdrawals during rainfall which might be have been a part of the calculation of the licence.
6. Even if supplementary and hidden water is physically mixed with the main intake withdrawn water, it could still be water deemed to be legally outside legal and licenced withdrawals (Mendoza-Espinosa et al., 2019). Clearly this a grey area for the legal ownership of different waters in ISA (Crow, 2019). For example, a farmer's use of rainfall or urban wastewater is to them 'ad hoc, informal and free', but a catchment regulator might deem this water to be an illegal withdrawal because officially it should be returned to the catchment. Both the physical sourcing/mixing of informal water with formal irrigation water and its legal status will have ramifications for how an irrigated system expresses itself via increases in area and/or volume depleted, and this in turn will depend on the governance of water in the catchment/aquifer.
7. Allied to the previous point, supplementary water sourced at lower scales (field and farm) might be seen by farmers to be hydrologically 'free' if there is little competition for that water at that scale and time and is refilled by wet-season rainfall. However, increased incidence of drought plus greater use of supplementary water across a longer duration will influence the wider hydrology of the basin (Glendenning and Vervoort, 2008; Scott et al., 2004). This magnifying effect will increasingly make in-situ and local water hydrologically and legally equivalent to formally withdrawn water with consequences for its regulation and its position within irrigated systems accounting.

3.3.5. *Case 11; large-scale seasonal storage*

An example of irrigation infrastructure, large dams act as inter-seasonal storage able to bank surplus water from the wetter part of the year and feed it to irrigation during the water scarce period (McCartney and Smakhtin, 2010). Depending on other variables, storage acts three ways on agro-hydrology and areas. (Section 4.1.8 discusses several pitfalls associated with accounting for large-scale storage).

1. In the 'storage for drought' version (11A), IE remains the same as the Baseline (45%) and a storage of approximately 1.0 hm^3 is released making up for the lack of rainfall. When rainfall is zero, the required season withdrawal (RSW) grows by 1.0 hm^3 which is met by 1.0 hm^3 of stored water added to the 4.20 hm^3 available from the intake. Depletion is the same as Case 1 at 3.85 hm^3. In 11A, the total zone area fed by TWW is 599 ha, 1 ha less than the Baseline.
2. In the 'no-drought, add to SSW' version (11B), rainfall is the same as the Baseline but the stored 1.0 hm^3 of water is added to the scarce season required withdrawals of 4.20 hm^3. With this total withdrawal of 5.20 hm^3 and the lower soil moisture deficit than 11A, 11B's total zone area rebounds to 741 ha, 143 ha greater than the Baseline's 598 ha, and 141 ha larger than 11A. However, total depletion of the scarce season withdrawals (which excludes the storage add-in) for 11B remains the same as the Baseline at 3.85 hm^3.
3. In the 'no-drought, replace SSW' version (11C), rainfall is the same as the Baseline but 1.0 hm^3 of stored water replaces some of the scarce season withdrawals bringing the latter down to 3.20 hm^3. This in turn reduces the total depletion of the scarce season withdrawals (which excludes the storage add-in) to less than the Baseline at 2.93 hm^3. Note the total volume withdrawn (TWW) ensures 11C's total zone area remains the same as the Baseline at 598 ha.

3.4. *Pareto-checked depletion-based reallocation*

ISA is able to compute reductions in total zone depletion to reallocate that water to other uses and sectors. These can be pareto-checked to not cut crop production. Six cases of reallocation are tested using the variables; area, withdrawals, duration, storage, return flows and an IP+II combination (Table 6). Each case is given as A and B versions (45% and 85% CIE respectively) to control for the effect of a higher CIE, making 12 cases in all. Each case is compared with the Baseline in Section 3.1 which produces 7854 tonnes maize from its aggregate area of 598 ha. It is this tonnage of production that the pareto analysis of depletion aims to sustain.

Thereafter two options[12] select inputs to start the pareto check on depletion. First an input can be manually entered an appropriate level. For example, in R1, a 10 % cut in area is applied. Second, alongside the change in selected variable (e.g. area), Excel's Goal Seek sets the withdrawal and IWO to peg crop production to the Baseline while anticipating a drop in aggregate depletion.

- Case R1 controls the primary and therefore total zone area. The primary zone is reduced by 10 % from the Baseline's 400–360 ha. When CIE is 45 % (R1A), a pareto-neutral reduction in depletion cannot be found. Using Excel's Goal Seek, an IWO of 0.39 hm^3 takes the total zone back up to 598 ha (same as Baseline T1) to produce the same production, withdrawals and depletion as the Baseline. This means no water can be reallocated to other users without harming crop production. In R1B, when CIE is increased to 85 %, a pareto-checked solution can be found giving withdrawal and depletion cuts of 1.10 hm^3 and 0.82 hm^3 respectively. Therefore, constraining area and raising IE provides real savings that are crop-production neutral. Berbel et al. (2015) also found cases of no depletion rebound when area is limited. A variation is to stop the total zone area from exceeding a threshold but in ISA this still involves setting the PZ area.
- R2 controls withdrawn water. With the 45 % IE version (R2A), no pareto-checked reductions in aggregate depletion can be derived. With the R2B's IE set higher at 85 %, a pareto solution can be found; withdrawals are cut by 1.10 hm^3 which delivers real savings of 0.82 hm^3. Summarising, Case R2B finds that withdrawals and depletion can be cut in ways that do not harm crop production provided a higher IE is achieved.
- Case R3 cuts the duration of irrigation by 10 % and uplifts the crop WUE by 5 % to compensate for an equal-yielding shorter-season variety. With 45 % CIE, this time-cut results in both withdrawal and pareto-checked depletion reductions for R3A of 6 % against the Baseline. With CIE increased to 85 %, R3B delivers a pareto-checked solution of the same crop tonnage but with − 30 % reduction in withdrawals and − 26 % reduction in total zone depletion.
- Case R4 uses storage add-ins of 0.5 hm^3 to substitute scarce season withdrawn water. Excel's Goal Seek can reproduce the same crop tonnage in both R4A and R4B. In the less efficient R4A, SSW withdrawals and depletion are both reduced by − 12 % compared to the

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[12] A third option is to use Goal-Seek to derive a selected target volume of water to be reallocated.

Table 6

Six cases of pareto-checked reductions in aggregate water depletion.

Case	Input variables	PZCIE	TZEIE	IWO	SSW	SSWC	SSWC	TZD	TZDC	TZDC	Crop	WDP	TZA	RUW	RUWC	Rank
	Units	%	%	Hm^3	Hm^3	Hm^3	%	Hm^3	Hm^3	%	T	T/hm^3	Ha	Hm^3	%	RUW
#1. Baseline	Baseline	45 %	73 %	0.00	4.20	NA	NA	3.85	NA	NA	7654	1988	598	1.47	NA	12
R1A. Prim. area	PZA −10 %	45 %	73 %	0.42	4.20	0.00	0 %	3.85	0.00	0 %	7654	1988	598	1.47	0 %	11
R1B. Prim. area	PZA −10 %	85 %	93 %	1.10	3.10	–1.10	–26 %	3.03	–0.82	–21 %	7654	2527	598	2.29	56 %	6
R2A. Withdraw	SSW no change	45 %	73 %	0.00	4.20	0.00	0 %	3.85	0.00	0 %	7654	1988	598	1.47	0 %	12
R2B. Withdraw	SSW −26 %	85 %	93 %	0.88	3.10	–1.10	–26 %	3.03	–0.82	–21 %	7654	2527	598	2.29	56 %	7
R3A. Duration	ITD −10 %	45 %	73 %	0.22	3.96	–0.24	–6 %	3.63	–0.22	–6 %	7654	2108	633	1.69	15 %	10
R3B. Duration	ITD −10 %	85 %	93 %	0.94	2.92	–1.27	–30 %	2.86	–0.99	–26 %	7654	2678	633	2.46	67 %	4
R4A. Storage	STOR 0.5 hm^3	45 %	73 %	0.00	3.70	-0.50	–12 %	3.39	–0.46	–12 %	7654	2258	598	1.93	31 %	8
R4B. Storage	STOR 0.5 hm^3	85 %	93 %	0.88	2.60	–1.60	–38 %	2.54	–1.31	–34 %	7654	3013	598	2.78	89 %	3
R5A. No reuse	RRR to 0 %	45 %	67 %	1.12	5.32	1.12	27 %	3.56	–0.29	–7 %	6492	1821	507	1.76	19 %	9
R5B. No reuse	RRR to 0 %	85 %	93 %	1.10	3.32	–0.87	–21 %	3.02	–0.83	–21 %	7654	2533	598	2.30	56 %	5
R6A. IP/II combo	IP/II x 11	45 %	73 %	0.34	1.81	–2.38	–57 %	1.66	–2.19	–57 %	7654	4602	633	3.66	148 %	2
R6B. IP/II combo	IP/II x 11	85 %	93 %	0.66	1.21	–2.99	–71 %	1.18	–2.67	–69 %	7654	6480	633	4.14	181 %	1

Abbreviations are defined in Table 1. Total areas (TZA) are derived from TWW.

Baseline. The more efficient R4B, pegged at the Baseline's production, delivers − 38 % and − 34 % reductions in withdrawals and depletion respectively.

- Case R5 tests the change in depletion when the reuse of recovered water from PZ is ceased, meaning RRR % is dropped from 75 % to 0 %. (For example, Tanzania specifies that return flows from irrigation should not be re-tapped by farmers, although practice this is widespread). Using Goal Seek to keep crop production the same as the Baseline, R5A (45 % IE) requires an IWO that exceeds the supply of the river. Thus, R5A matches withdrawals to the river supply but sees a cut in crop production of 15 %. The more efficient R5B does better; Goal Seek produces a solution giving the same production as the Baseline yet delivering − 21 % reductions for both withdrawals and depletion.
- R6 tests changes to 11 IP and II variables to manage soil-crop ET and utilise 0.5 hm^3 storage. R6A, with an IE of 45 %, delivers both paper and real savings of 57 %. R6B with the higher IE produces 71 % and 69 % paper and real savings respectively while sustaining crop production at the baseline level. This combination of variables is very effective in delivering pareto-checked real water savings.

4. Discussion

4.1. Are we mis-paradoxing irrigation efficiency?

Describing irrigation water conservation via a single irrigation efficiency paradox narrative may be misleading. We can probe whether one irrigation efficiency paradox is operating, and ask if one explanation unhelpfully conflates myriad hydrological changes? Section 4.1 argues that by over-simplifying the agro-hydrology of irrigation undergoing change, we could be mischaracterising or mis-paradoxing it.

4.1.1. One, many or contradicting paradoxes?

Reflecting on the cases in this paper, there are many water conservation outcomes produced by diverse agro-hydrological variables and relationships. Whether these outcomes are deemed by future consensus to be individual paradoxes is a moot point. However, they provide an opportunity to ask whether one irrigation efficiency paradox explains them all.

Grafton et al. (2018) refer to one paradox in their paper's title and main text. Cai et al. (2023) and Ilyas et al. (2021) also refer to one paradox. Grafton et al.'s explanation appears to refer to Case 2 'paper versus real savings' paradox which in turn builds on Case 1′s cross-scale reuse of losses. They write on page 748; "*and an increase in IE that reduces water extractions may have a negligible effect on water consumption. This paradox, that an increase in IE at a farm scale fails to increase the water availability at a watershed and basin scale, is explained by the fact that previously nonconsumed water "losses" at a farm scale (for example, runoff) are frequently recovered and reused at a watershed and basin scale.*"

While Grafton's paper correctly focusses on water depletion across the total zone (representing the basin), its explanation needs more information to be an accurate generalisation. There are several reasons why 'one irrigation efficiency paradox' requires careful elaboration. First, except for Case 3 where 100 % of losses are fully recovered, ISA's calculations refute "*increase in IE that reduces water extractions may have a negligible effect on water consumption*". For example, Case 2, with its credible selection of irrigation efficiency ratios in keeping with suggestions by Grafton et al. (2018) shows that by increasing CIE from 45 % to 85 %, water withdrawals and total zone aggregate depletion decrease by similar amounts (47 % and 44 % respectively). Furthermore, all the higher efficiency 'B′ cases in Section 3.4 correlate reductions in withdrawals to cuts in depletion provided other variables are constrained. Additionally, Case 12 (below) reveals higher IE reduces withdrawals and depletion when return flows are small.

Second, a flaw arises between the two arguments often seen when discussing the paradoxical effects of raising irrigation efficiency. The two arguments are; 'a higher IE has no effect on depletion' and 'a higher IE increases depletion'. The problem is these are markedly different outcomes which contradict each other. Grafton et al. (2018) argue that when most or all irrigation losses are reused, higher efficiency rarely reduces water depletion. Note, a view on high recovery is also given by Van Opstal et al. (2021) on page 7 "water is never lost" and by FAO (2017, p.35)[13]: "*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.*" These views say withdrawn water not crop evapotranspired is nearly all recovered and is eventually evapotranspired giving a far greater irrigated area and depletion than explained by the initial water withdrawal process.

However, total 'within time' depletion of all recovered losses precludes an 'over time' rebound of area and depletion. Yet in both the Grafton paper and in FAO (2017, p 35–36) a higher IE is said to be behind a rise in depletion: "*For the farmer, hi-tech irrigation allows some combination of increased irrigated area, increased quantity of production, and increased value of production. But in parallel with these benefits, current water consumption is likely to increase (with consequent decreases in return flows), and future demand for water will increase because water is a more valuable input to the far*mer". Case 3 demonstrates the two outcomes cannot coexist. With 100 % recovery of all losses, '3Base' (CIE = 45 %) already depletes all the water throughout the total zone which means a rise in IE (to 3A's 85 %) does not increase water depletion. For depletion to increase under a higher IE requires Cases 4–6 where an IWO exists, but FAO (FAO 2017, p 35–36)) and Grafton et al. (2018) make no

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[13] See also FAO (2020, p.65).

reference to whether withdrawals remain 'as before' via an IWO. In other words, 'no change' versus 'an increase' in depletion requires different conditions. Unless these conditions apply, the corollary of 'a higher IE does not reduce water depletion' is 'a higher IE does not increase depletion'. Furthermore, some over-time increases in depletion are not caused by reusing return flows, a point picked up in the next paragraph and in Section 4.1.2.

Third, it is important to identify, in a sequence of events, whether one or several causes-and-effects are occurring. Grafton et al.'s explanation of 'one paradox' seems to view the within-time recovery paradox as the cause or originator of the over-time IE-induced paradoxical change. While these interconnect, they are separate. Case 4 illustrates; 'before an efficiency gain' the Baseline sees an extra 198 ha irrigated on top of the primary 400 ha via recovered losses bringing the total to 598 ha. After an efficiency gain, Case 4′s total zone area increases to 810 ha from the same withdrawn water as the Baseline. But Case 4′s reuse zone has shrunk from 198 to 54 ha because it is a residual of the more efficient and expanded primary zone which is now producing fewer recovered losses. Although the primary, expansion and reuse zones are interconnected via 'losses changing over time', the recovery of losses in the reuse zone is not causing the hydrological change in the primary + expansion zone combined. With full recovery/reuse (Case 3A) a rise in IE witnesses the expansion and reuse zones trading places. Keller and Keller (1995) also make this point (page 11).

Case 3A and its twin 3B reveal another pitfall; if 100 % of local losses are reused, aggregate depletion takes place via crop beneficial consumption regardless of the change in IE. Seen in Appendices A and B, the total zone effective irrigation efficiency (EIE = NIR/depletion) is 99 % for both 3A and 3B. Yet it stretches credulity that a total zone system in the real-world with a CIE of 45 % performs nearly identically in area, ET and depletion as a system with 85 % CIE. This is why the generalisation that losses are mostly recovered must be questioned. Despite strong parallels being drawn (Perry, 2007; Perry et al., 2023), irrigated systems are not urban systems where water supplies and wastes are nearly all piped, and losses are rapidly returned to the sewage/water system. Other pitfalls associated with recovered flows are discussed in the next sub-section.

4.1.2. *Case 12; over-emphasising the role of return flows*

Explanations of the IE paradox stress the importance of the changes in the recovered fraction under an improving efficiency (Grafton et al., 2018; Perry et al., 2023). This can be questioned in a number of ways. Cases 12Base, 12A and 12B reveal two 'low recovery' pitfalls that say these explanations over-emphasise the salience of return flows in explaining paradoxical outcomes. Case 12 says irrigation expansion instead occurs via the use of non-recovered and non-beneficial consumption. Case 12 employs a 10 % recovered fraction ratio (rather than >60 % as in Cases 1–6). Thereafter losses are divided equally between non-beneficial consumption and non-recovery. Case 12 establishes a baseline (12Base) against which 12A and 12B are compared; 12Base has a CIE of 45 % whereas 12A and 12B both use 85 % CIE. Case 12A allows 12Base's withdrawal to continue, giving an IWO of 1.97 hm^3 but 12B does not apply an IWO (withdrawals are cut compared to 12Base).

By removing the existence of the reuse of return flows, Case 12Base and 12A challenge the paradox that 'no change in depletion is the result of return flows being reused'. Switching to a higher IE of 85 %, but sustaining the same withdrawal as 12Base, 12A paradoxically witnesses a near-identical aggregate depletion (4.18 hm^3) as 12Base (4.14 hm^3) and an increase of 77 % in area. In other words, the primary zone uses NBC and NRF to expand crop beneficial consumption in the primary + expansion zone combined.

Case 12B, which does not apply an IWO, presents another pitfall because when recovered losses are minimal; water withdrawals and depletion align (an observation also made by Pérez-Blanco et al., 2020 on page 221). With less water withdrawn and not recovered, increasing CIE from a lower value of 45% up to 12B's 85% creates equal paper and real savings of 47 %. This situation counters arguments that; a) raising IE and cutting withdrawals have no effect on depletion; and b) reductions in return flows explain changes in agro-hydrology.

Substantively, Case 12 questions whether large return flows created by over-irrigating farmers continue to be a meaningful explanation when characterising agro-hydrological change. Case 12 may accurately reflect present-day semi-arid catchments experiencing periodic drought and intense inter-farmer and inter-sector water competition. In other words, even without the adoption of drip irrigation, large irrigation return flows may no longer be a major feature of recent and contemporary agro-hydrology.

Finally, the emphasis given to return flows in controlling the difference between withdrawals and depletion is also questioned by comparing Cases 3A and 3B in Section 3.2.3. Here, even with 100 % full recovery of return flows, reducing withdrawals in 3B by 47 % (no IWO applied) cuts depletion by 47 %. The chief cause of the difference in agro-hydrology between 3A and 3B is the cut in withdrawals to 3B rather than the presence and action of recycled losses.

4.1.3. *Depletion is zone- and scale-related*

Depletion is zone-related. When IE increases, water depletion occurs differently across the primary, reuse and expansion zones. This means cutting depletion at the farm scale (primary zone) does not equate to cutting depletion at the basin scale (total zone). This is a more precise exposition of Case 2′s difference between real versus paper savings, but the importance of per-zone accounting is highlighted. In Case 2, real savings were less than paper savings only in the primary zone but they were nearly the same across the total zone. This means that paradoxes are scale- and zone-defined. This is a pitfall to scientists who, despite underscoring the difference between reducing withdrawals (paper savings) and reducing depletion (real savings) and the importance of basin level accounting (Jovanovic et al., 2020; Siderius et al., 2022; Törnqvist and Jarsjö, 2012; Van Opstal et al., 2021), either do not distinguish between farm-level and basin-level depletion nor explain how the latter connects to, or arises out of, the former. Furthermore, this lack of equivalence is not pro rata; 10 % real savings on a 100-ha farm scaled up do not give 10 % real savings in a catchment with 1000 ha of irrigation. Case 4 also evidences this pitfall; primary zone depletion went down (real savings of 28 % occurred at the farm scale) but depletion went up for the total zone by 7 % (real savings failed to materialise at the basin scale).

4.1.4. *Withdrawals, applications, farm depletion, basin depletion*

Elaborating the previous section's point, Appendix A quantifies the Introduction's pitfall of the need to clarify whether paper savings are either reductions in 'a′ water withdrawals (SSW) or 'b′ field applications (with two types, PZFA and PEZFA), and real savings as the difference between 'c′ farm water depletion (PZD or PEZD) and 'd′ basin water depletion (TZD). Analysis shows these differ and disproportionally vary according to circumstances. Appendix A Section 3.6.3 continues the discussion, particularly regarding some confusions surrounding paper water savings.

4.1.5. *Paradox inverted, higher IE reduces depletion*

The depletion rebound from a higher IE can be inverted when other variables (such as area, withdrawals, and duration) are controlled. Accordingly, in all the 'B′ Cases in Section 3.4, an improved IE underwrites depletion-based water savings while sustaining crop ET. For example, Case R1B executes a pareto-neutral depletion-reduction of − 21 % by irrigating 90 % of the primary zone area accompanied by cutting withdrawals to match. By controlling other variables, the benefits of a higher CIE counter these two statements which leave additional factors unstated or uncontrolled; "…*in a basin with an already high degree of water reuse, improved project efficiencies will not help much to increase the availability of water for new irrigated areas within the basin*" (Döll and Siebert, 2002) (page 8); and "*increased IE rarely delivers the presumed* *public-good benefits of increased water availability*" (Grafton et al., 2018). (p 748).

4.1.6. Specifying withdrawal caps (with Case 13)

Continuing the previous point, controlling withdrawals helps deliver depletion-based reallocation, agreeing with; "*increasing irrigation efficiency can lead to increases in aggregate water depletion unless the efficiency investments are underpinned by behaviour change and a cap on water extraction*" (Garrick et al., 2020; p 2). However, to effect desirable outcomes, withdrawal caps need to be understood and specified:

- Revealed by the six reallocation cases in Section 3.4, the volumes of IWO and SSW vary according to; a) control of other variables; and b) the pareto-neutral drop in depletion sought. Thus, withdrawal caps may have to be uniquely specified according circumstances and objectives.
- Capped withdrawals should not imply 'the same as before'. If withdrawals are not reduced in line with a smaller GIR, its continuation leads to an IWO which, combined with a higher CIE, raises depletion. Case 4′s withdrawals are maintained at the Baseline's 4.20 hm^3, yet Case 4′s total depletion increases from the Baseline's 3.85 hm^3 to 4.10 hm^3. Case R2, on the other hand, cuts withdrawals by − 47 % and sees a similar cut in depletion of − 44 % across the total zone.
- Flow rates versus volumes should be distinguished. Compared to Case 1, Case 6 reduces withdrawal flows from 0.347 m^3/s to 0.191 m^3/s which looks like a reduced cap or rate of withdrawal. But Case 6′s higher IE translates into a longer 254 days of withdrawals with the result that it withdraws 4.20 hm^3, the same volume as Case 1. However, as one of the rebound paradox cases, depletion in Case 6 rises to 4.10 hm^3, up from 3.85 hm^3 in Case 1. The contrast is stark; a lower withdrawal flow rate yet greater total depletion.
- Withdrawal caps to reduce depletion should account for how water from seasonal storage is deployed. Discussed in Case 11, an either/or arises; either water releases from dams add to withdrawals which paradoxically induce higher total areas and depletion. Or releases from dams replace (i.e. cap) withdrawals during dry periods which cuts scarce-water depletion.
- A river basin may experience pinch periods when weekly or monthly scarcity occurs. This means 12-month volumetric caps will be too coarse to resolve competition for water. Designing caps and infrastructure should recognise and respond to marked variations in supply (Lankford and Mwaruvanda, 2007).
- Believing excessive withdrawals are of no significance if they are hydrologically compensated by return flows from inefficient irrigation is a pitfall. Aside from the costs outlined in Section 4.1.9, this is because large withdrawals are constrained by intake dimensions. The low efficiency of Case 13 generates large recovered flows which should give a total area similar to Case 1. However, Case 13′s low CIE (set at 10 %) results in a total area 74 ha smaller than the Baseline. This occurs when the gross irrigation requirement notionally increases to meet that low efficiency but which then exceeds the intake capacity or available scarce season supply. The corrected season withdrawal (CSW) adjusts for this, setting the withdrawn water at the SSS of 5.32 hm^3.
- Even though formal withdrawals at the intake may be capped, real-world withdrawals and depletion can increase by using informal and hidden water (see Case 10 in Section 3.3.4).

4.1.7. Case 14; pitfalls regarding area and depletion

Space precludes a full analysis of the factors driving irrigated area and depletion, however some thoughts can be offered about the relationships involved:

- ISA's cases reveal area and depletion can change independently contingent on agronomic, infrastructural, operational, and agrometeorological factors in addition to irrigation efficiency.
- Area growth is particularly sensitive to the management of soil-crop ET. Case 14 applies no IE uplift and withdraws the same water as the Baseline. But via relatively small changes to soil moisture and informal water management, it irrigates 1255 ha (110 % above Baseline). This introduces three pitfalls. First, the growth of citrus in South Africa outlined above is partly explained by greater use of ET modification and of in-situ, informal, hidden and stored water (Lankford et al., 2023), not the reduction in return flows. Second, area can increase without depletion increasing. Third, Case 14 asks whether area rebounds are incorrectly attributed to CIE rather than to the management of soil-crop water.
- Case 9 in Section 3.3.3 raises the question of how to define an irrigated area. There are two points. First, the primary irrigated area in hectares depends on its provenance drawing on farmer opinion, maps, farm records, satellite analysis, aerial photography and land surveying. These all carry a margin of error which may not reflect the second error. This is that minor changes located by irrigators checking their fields in order to cease watering parts of them might not inform official figures. The pitfall for auditors is that the 10 % marginal cessation of irrigation within parts of fields is not spotted but the mapped rebound of 10 % is recorded.
- Related, while satellite imagery might show an area increase, this may not discern how this has taken place via micro-scale management of soil-water at the field scale, informal supplementary water, large-scale storage, or via irrigation efficiency. For real-world irrigation systems undergoing overlapping natural, physical and human changes, it is risky to ascribe depletion and area rebounds to one or few factors.
- Cutting irrigated area cuts withdrawals and depletion. This is no surprise given its centrality in the equation; 'volume = depth equivalent x area' – see also Puy et al. (2021). Although irrigated command area is an infrastructural choice, this is a possible pitfall because area as a driver of changes in hydrology (rather than a consequence) is rarely discussed in the literature (Lankford et al., 2023). For pareto-neutral effects of cutting area, refer to Case R1B.

4.1.8. Pitfalls associated with large-scale storage

Large water storage poses six challenges to the hydrology calculations and paradoxes regarding area, withdrawals and depletion. First, options for the release of stored water affect agro-hydrology, as seen in Cases 11 and R5. These options can evolve over time and need to be tracked. A dam, initially designed to compensate for drought, may increasingly release water throughout the agrometeorological calendar. Second, storage-induced areal rebounds can be achieved without invoking a higher IE. Third, storage can meet seasonal volumetric withdrawals (hm^3) yet keep daily flow withdrawals within required limits (m^3/s) set by the intake design and catchment supply and demand. Fourth, storage offers opportunities for re-allocation by alleviating pressure on water resources during the scarce water period (Case R5). Fifth, related to the last two points, large-scale storage unpacks the meaning of 'total withdrawals and depletion'. It is mathematically correct to state 'total volumes' occur across 12 months of a typical hydrological year. But it is more water-management savvy to focus on the non-wet period (say 6–10 months) when water scarcity is more pronounced and withdrawn shares in percentages or flow rates (m^3/s) trump concerns over aggregate annual volumes (hm^3). Picking up on the fifth point, Case 11 throws up the question of what water should be accounted and for what reason. One option calculates all water withdrawn (i.e. season-critical volumes plus wet season additions), another focusses on scarce season withdrawals if storage add-ins are deemed hydrologically 'free'. Likely to depend on circumstances, ISA currently focusses on the latter; it finds allocatable water based on reducing the depletion of the 'scarce season' withdrawn water (SSW).

4.1.9. Recovery of irrigation losses is not costless

There are at least 10 externalities or costs associated with water losses in inefficient irrigation even if these are mostly recovered. Mitigating these are "Appropriate Reasons to Conserve Water by Increasing "Efficiency" (Uniformity) of Water Application" (Allen et al., 2005 p 5). Referred to by a number of authors (Allen et al., 2005; Lankford, 2006, 2012; Seckler, 1996), over-irrigation in a low-CIE system brings harms and costs. A low CIE; sharpens water inequalities between farmers and between irrigation and ecological systems; raises the costs of pumping and treating water; slows irrigation scheduling; risks soil erosion, waterlogging, nutrient leaching and salinisation; results in poorer quality drainage water; warms surface waters; undesirably distributes water within segments of streams, aquifers and catchments; and via coupled effects leads to more water becoming unavailable. The latter sees low efficiencies resulting in higher evaporative loss as a form of ullage that falls to no party. Nearly all 10 costs negatively impact crop productivity thereby strongly connecting IE to the yields, economics, sustainability and livelihoods of irrigated production. While these costs might be manageable or become accustomed to by basin actors and ecologies, they bring discriminatory effects. In other words, recovered losses in irrigated systems do not seamlessly translate into equally productive irrigation or ecosystem services elsewhere. ISA does not currently model these externalities.

4.1.10. *Paper savings are not paper flows*

Policy-makers are being asked to seek real savings in ways that undermine the role of paper savings – see for example Van Opstal et al. (2021). This is a false choice because paper savings involve real flows and effect real savings. To illustrate; is fixing canal leaks a real or paper saving? The answer is they are both, and are coupled and location-specific (Lankford, 2012). Although water accounts draw attention to depletion of water by irrigated systems, these accounts do not necessarily tell us how to manage real flows. While Uhlenbrook et al. (2022) correctly prioritise depletion as the ultimate arbiter of reallocation out of irrigation, what is worrying is they conclude on page e64 consumption caps should replace, not sit alongside, limits on withdrawals. Irrigation infrastructure (likely ageing, and poorly operated and maintained) that only allows consumption does not exist except perhaps in hydroponic greenhouses. Capping consumption or managing real savings are not instructions that can be handed to canal gate-keepers.

4.1.11. *A fallible ratio – how you like it*

The dimensionless CIE ratio hides useful information, and thus the causes and consequences of its increase can be argued variously. Employed solely and unquestioningly, it is fallible. More than one change causes it to increase (Ward and Pulido-Velázquez, 2008). It increases if the numerator (beneficial consumption) increases or if the denominator (withdrawal) decreases or if both happen simultaneously. Furthermore, the CIE ratio; hides that its component volumes are far from dimensionless; ignores the significance of recovered flows; imprecisely defines beneficial consumption; is not easy to measure and judge; normatively implies 100 % is a target; and fails to capture other dynamics (Section 4.1.9). These and other fallibilities of the CIE ratio have been long discussed (Keller and Keller, 1995; Lankford, 2006; Perry, 2007; Solomon and Burt, 1999). In the face of this, how do scientists interpret the CIE ratio? Using Baselines and cases from ISA, and depending on other often unstated variables, a rise in CIE from 45 up to 85 % illustrates at least five different arguments:

1. An increase in CIE saves water (Christian-Smith et al., 2011) revealed by Case 2′s drop in both withdrawals and aggregate depletion.
2. Raising CIE has no effect on water savings (Grafton et al., 2018) demonstrated by Case 3A's 100 % full recovery of return flows, provided withdrawals are not cut in line with a lower GIR.
3. An increase in CIE boosts water depletion (Ward and Pulido-Velázquez, 2008) shown by Cases 4–6 where an IWO is applied.
4. A higher CIE "Maximize[*s*] the total fraction of water delivered to crops to increase crop yields" (Allen et al., 2005 p 5). In Case 2, compared with Case 1, total zone withdrawals, depletion and beneficial consumption all decrease but BC increases in proportion to withdrawals and depletion.
5. Demonstrated by Case 4 (see Appendix A 3.6.3), an increase in CIE reduces field water applications in the primary zone by mm depth and by volume, yet increases field water applications by volume across the primary and expansion zone combined.

4.2. *Weaknesses in current irrigation accounting*

4.2.1. *Water accounting; few or many moving parts?*

The relative lack of irrigation management information in the IE ratio necessitates water accounting (Perry, 2007; Seckler, 1996). In other words, IE alone cannot be relied on to guide reductions in depletion without the qualifications offered by WA. By extension, ISA finds WA lacks important water information. WA has only four final dispositions of withdrawn water and contains no reference to many other variables, ratios and relationships that shape soil-crop moisture, withdrawals, depletion, and non-use of water over space and time. The question for water accountants is whether irrigated systems are simple and can be approached via Occam's razor whereby entities are reduced in number. Or, containing many moving parts, Hickam's dictum is more relevant. An answer to this complexity dilemma (Nolting and Praktiknjo, 2021) sits with how models unpack system dynamics. A simple model with few variables should comment on few system variables, or inadequately explain many system variables. 'Should' is written here because what seems to be happening is that by being simple, the now 30-year-old WA (Willardson et al., 1994) is expeditiously malleableised to comment on diverse agro-hydrological phenomena. While this is testament to its strength as a descriptive-explanatory model, authors (FAO, 2017; Grafton et al., 2018; Van Opstal et al., 2021) who introduce the WA schema in their articles rarely employ it to fully quantify those phenomena.

4.2.2. *Gaps between explanations and water accounts*

Water accounting systems with few variables struggle to support detailed explanations of hydrological change. Explanations omit how a rebound paradox precisely occurs indicating which variables are fixed and which vary. Instead the irrigation efficiency paradox literature uses terms such as 'modern irrigation', 'water productivity', 'efficiency' to explain how rebounds take place; "*In addition, as modern irrigation incentivizes farmers to switch to higher-water-consuming crops, expand cropping areas or increase cropping intensity, this raises farmers' incomes but also water consumption*". (FAO, 2020, p.65). Whilst credible, this does not quantify how depletion increases as a result of modern irrigation.

A related omission occurs when variables are introduced without explaining how they create a rebound paradox. For example, it is not clear how water productivity (WP), as the ratio of the yield per water withdrawn or depleted (kg/m^3), physically drives up water depletion since; a) the WP ratio includes the yield of the crop which depends on many other factors; and b) the hydrological part (m^3) of the WP ratio is often not defined as being withdrawn, field-applied, farm-depleted or basin-depleted water. Writing; "*In fact, an increase in water productivity frequently has the perverse effect of increasing demand for water: the farmer can afford to pump more water from a deeper well if the productivity of that water increases*", Van Opstal et al., (2021, p.6) do not define "demand for water" and fail to explain how the WP ratio leads to more water depleted. There is nothing intrinsic about irrigation technology or economic returns to water that increases depletion unless that logic is fully explained and quantified.

4.2.3. *The messy middle is not served by opposites*

Applying one unalloyed side of the dual nature of a paradox (raising IE does not save water or drives up depletion) to address the opposite unalloyed side of that paradox (raising IE saves water) does not suit where most irrigated systems sit; in the messy middle. It is unsatisfying because it is a dispute between two polar opposites that rely on a specific reading of IE regardless of circumstances. The middle cannot be represented by an idealised hydrology of irrigation systems where either classically all losses need not be accounted for, or paradoxically all losses seamlessly recycle to the basin. This author is not confident that polarised debate brings benefits for people, irrigation systems and basin sectors appealing for increasingly scarce water. Furthermore, this concern deepens because few water research, policy and funding bodies seem able or willing to navigate the messy middle. Depletion-based pareto-checked water savings that carry low transaction costs are difficult to solve and even more difficult to deliver. Resolving outcomes in this middle needs our full attention.

5. Conclusions

ISA derives crop-production-neutral depletion-based savings by raising irrigation efficiency combined with; tailored withdrawal reductions; control of irrigated area and duration, careful application of soil, crop and irrigation practices; and the judicious use of informal water, storage and other infrastructure. ISA achieves this by modelling per-zone and total zone (aggregate) variables and relationships of irrigated systems evolving over time and space. The ISA model helps resolve efficiency paradox arguments based on few variables (e.g. ET and return flows only) that raising IE brings no real savings or higher depletion. The paper argues that the terms ‘real savings and paper savings’ can be problematic unless defined in volumetric terms carefully tied to system-level, zone, time and scale reference frames.

Facing a crucible of challenges – water reallocation, crop production, climate change and energy – the considerable volumes of water withdrawals and depletion in irrigated catchments increasingly demand our attention (Elliott et al., 2014; Sadoff et al., 2020). In this crucible, the changing roles of irrigation efficiency, practices and infrastructure are playing out over scales and time. If multiple and overlapping causes of, and inputs to, agro-hydrological change are fully accepted, three insights follow:

1. Where relevant, policies must promote and guide excellent frugal irrigation management.[14] This is management that involves farmers, sustains or raises crop production, improves water equity, and resolves irrigation efficiency paradoxes in order to reduce aggregate water depletion. Excellent management, especially in systems not amenable to drip irrigation, is not asking for efficient water management where this does not control withdrawals and depletion. That said, we should not berate calls for efficient irrigation as they intend higher crop production with less not more depletion.
2. We should elevate the significance of real flows of water and withdrawals in irrigated systems alongside aggregate depletion as we further debate water management and reallocation.
3. To serve these many challenges, excellent irrigation management should be supported by accounts and approaches that are system-wide, multiscale, multifactorial, tailored, context-specific and long-term. Accordingly, depletion-based reallocation should control for different IE, IP and II interventions individually customised to irrigated systems and their farmers and managers.

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Declaration of Competing Interest

I declare that I have no conflicts of interest regarding the authorship, submission and publication of this paper.

Data Availability

Data will be made available on request.

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Appendices A and B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108437.

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[14] Building on Chamber’s call for a ‘new professionalism’ in irrigation (Chambers, 1988) or Lankford’s term ‘actualising management’ (Lankford and Gowing, 1997).

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