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Fictions, fractions, factorials and fractures; on the framing of irrigation efficiency

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ABSTRACT

Irrigation efficiency, as a complex and useful measure of irrigation performance, is in a vulnerable scientific position. Knowledge gaps feed through to naïve views of a sector held to be highly inefficient, 'wasting' freshwater which could be allocated to other purposes. Confusions and lack of evidence allow room for policy errors – for example the notion that micro-drip technology should replace surface canal irrigation – and underpin an incomplete scientific debate over whether recoverable losses matter resulting in a dismissing of classical irrigation efficiency. Thus with regards to the water challenge of how and why to improve efficiency, society finds itself facing multiple risks; errors in terminology employed, poor engagement with local users on the issue; inappropriate computational methods and a lack of well-executed analyses to challenge commonplace views. In addition, the nuances of an 'efficiency and productivity' debate seem not to feed through to interest groups; engineers continue to think in classical terms when not appropriate; incomplete science does little to inform serious policy-making; and scientists seem unable to agree on methods of performance assessment. This paper explores these fault-lines and tensions by taking the view that local losses and classical efficiency matter, and postulates that irrigation systems are locally individuated and have particular distributional and bifurcating properties. As a contribution to the debate, and in framing efficiency, two paradigms are discussed; 'basin allocation irrigation efficiency' utilising fractions and effective efficiency, and; 'socialised localised irrigation efficiency', utilising classical efficiency.

1. Introduction

> "*Egyptian water experts say that upstream countries waste colossal amounts of water that run off unused into swamps. The upstream countries point to Egypt's own wasteful practices, saying that 75 percent of Egypt's water is used for agriculture, most of it wasted by old fashioned practices. Despite periodic government efforts to promote less wasteful practices, irrigation water still flows largely through dirt channels choked with weeds.*" (*New York Times, 3rd Oct 2010*).

This quote reveals four dimensions regarding the debate about irrigation efficiency and productivity. First; "waste" is a term with political as well as scientific meaning; second, experts (it is reported) and journalists hold views regarding the amounts ("colossal") of both use and waste; third, practices ("old-fashioned" and "dirt channels choked with weeds") infer levels of performance; and, fourth, unused water ("into swamps") is lost to the system rather than being used beneficially elsewhere – in this case ecologically. While the New York Times describes tensions in the Nile Basin in this manner, what is worrying is that simplified views of efficiency are held by an array of stakeholders with knowledge and interests much closer to the problematic of the management of irrigation and host river basins.

Given this topic can be dissected in many ways; I place this paper within the debate on classical efficiency. My concern, indeed the substantive inspiration of this paper, relates to arguments that base their logic on the assumption that 'paper water savings' (recoverable water lost to a farmer, but recaptured by the river basin) need not be part of efforts to raise irrigation performance and productivity (Seckler, 1996; Molden et al., 2010), or that if irrigation efficiency is raised this feeds through into greater depletion (Willardson, 1985; Heaney et al., 2006; Ward and Pulido-Velázquez, 2008; Foster and Perry, 2010). I shall call this viewpoint, the first of two paradigms, 'basin allocation irrigation efficiency' (BAIE). I argue both in the Lankford (2006) paper and here, that the BAIE model with an emphasis on the volume of the consumptive fraction of irrigation water (and effective efficiency calculations) is in sharp contrast to an alternative 'socialised localised irrigation efficiency' (SLIE) viewpoint. The latter reflects a complex mosaic of multiple irrigation units inhabited by irrigators with livelihoods connected to crops awaiting their next dose of water – and who are connected to their neighbours via networks of shared water supply and consumption. In the SLIE model, local recovered losses

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and classical irrigation efficiency (CIE) remain of interest to irrigators and those managers, scientists and donors wishing to support irrigation.

My alliterative title 'fictions, fractions, factorials and fractures' captures signature components of a political ecology[1] of natural and managed systems of natural resources – in this case irrigation. 'Fictions' describe environmental myths regarding efficiency and losses arising from lack of detailed knowledge or pursuit of rigid conceptualisations amongst those connected to irrigation. 'Fractions' explain the key theoretical progress made in the last few decades – offering great insight but potentially masking the merits of a conventional framing of irrigation efficiency. 'Factorials' define the problematic method commonly used to estimate classical efficiency. 'Fractures' hints at the mental model by which scientists characterise irrigation systems and the water flows and losses which underpin the two main paradigms.

With regards to the scope of this paper, I do not propose to explore the history of irrigation efficiency – others have done this admirably (Jensen, 2007; Perry, 2007; Halsema and Vincent, in this issue). Neither do I offer views on the rise of 'fractions' and parallel dismissing of classical efficiency on the basis of anecdotal knowledge I have regarding communications between myself and some the parties involved. Neither shall I address the merits of water productivity as a concept to replace efficiency (CAWMA, 2007) or the definitional issues around 'water use efficiency' (see Howell, 2001; Lankford, 2006; Halsema and Vincent, in this issue; Pereira et al., in this issue, for a discussion on this). I shall also not directly address the methodologies employed recently by scientists to quantify the water footprint of crops (Hoekstra et al., 2011; Chapagain and Hoekstra, 2008) – although results are connected to method and assumptions.

Neither do I wish to analyse institutional identities associated with irrigation efficiency, except one can record the International Water Management Institute (IWMI) closely associated itself with new ideas of 'real' and 'paper' water saving (Seckler, 1996), calling it the "IWMI paradigm" at one point (Perry, 1999). IWMI now works on a set of modified fractions for the purpose of basin accounting (Molden and Sakthivadivel, 2006; Karimov et al., submitted for publication).

Furthermore, in offering a classical efficiency response to 'effective efficiency and fractions', my paper is far from being a deconstruction of the political ecology of, and motives behind, the framing of irrigation productivity and efficiency in the manner that Mollinga (2010) draws for water management in India or that Vos and Boelens achieve in this special issue. I also do not provide an analysis of the narrative of the low irrigation efficiency of surface irrigation systems because although command areas are generally larger than can be explained by low efficiencies, this requires field evidence to counter this argument and is beyond the remit of this paper. Nevertheless, I believe systems are more efficient (in the classical sense) than reported, yet it to be in the strategic interest of government irrigation departments to argue that efficiency is 40% or less in order to seek funding or to solicit farmers as a voting constituency via infrastructure subsidies.

I offer a revalidation of 'classical efficiency' in irrigation by examining the 'systems' nature of irrigation. This continues with, but adds new material to the Lankford (2006) paper. It is through these two papers, that I argue a basin-allocation-efficiency approach alone, eliminating classical efficiency (Willardson et al., 1994; Haie and Keller, 2008), offers insufficient opportunities to improve water management – particularly if we comprehend irrigation systems as comprising bifurcating competing units/users nested in larger groups of competing units. Furthermore, when we discern irrigation systems in trajectories of improving or declining water management we might acknowledge the constancy of change in irrigation efficiency. Properly assessed, efficiency should reflect the transitive fugitive nature of water and its fractions, making a single absolute measurement of irrigation efficiency problematic. Too frequently when differences in efficiency are postulated it is between surface and drip irrigation,[2] rather than in relative terms between surface irrigation from time period 'a' to 'b' or top-enders versus tail-enders. It should be the case that when terms are used to justify intervention directions they are understood to be complex, locally relevant and requiring trustworthy metrics to support assertions.

In characterising debates on irrigation performance, I initially sought to build a framework of understanding efficiency using Garvin's (2001) distinction of three realms of 'the public', 'policy-makers' and 'scientists'. However, this tripartite categorisation omits two other realms – practicing and commissioning engineers/operators and irrigating farmers. Yet more importantly, because I observe across all five realms similar misunderstandings reproduced in different literatures, I conclude that the minor distinctions between the realms insufficiently explain the current state of affairs in irrigation efficiency science. Recent science debates on irrigation efficiency (distinct from productivity) remain sufficiently marginalised not to make their way into public and policy arenas except in highly distilled and unhelpful forms as evidenced by the quote at the start of this article. The retreat from irrigation research (World Bank, 2006) has severely reduced or undermined the prospect for one realm to engage and energise the others. I am hesitant to ascribe a public understanding of irrigation performance because I do not witness a non-farming/urban public taking much interest in irrigation. Often, efficiency improvements are associated with technological recommendations that are not fully tested in the field. For example, donors and science organisations lean towards micro-scale irrigation water control through the use of bucket and drip systems (Belder et al., 2007). While these supposedly extend food security to households, the new technology infers higher levels of performance and precision. Furthermore, there are very few papers that capture irrigator concepts of their 'systems' efficiency and productivity *alongside* personal irrigator views of their own or immediate neighbours' efficiency or engineering concepts of efficiency. In that respect, I do not recall witnessing government or consultant engineers using farmer practices as starting points for irrigation rehabilitation, favouring instead their own expert perspectives (see Vos and Boelens, in this issue, for further exposition of this observation).

2. How and why we disagree about irrigation efficiency

2.1. Introduction

I take the view that there are essentially two paradigms of irrigation efficiency each dependent upon a particular ratio computation (Fig. 1). First, under a model I have termed 'basin allocation irrigation efficiency' (BAIE), effective irrigation efficiency (EIE) (Keller and Keller, 1995; Keller et al., 1996) captures the ratio of beneficial crop evaporation (numerator) to the denominator of total depleted water (including non-consumed water but cannot be

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[1] Here 'political ecology' is taken as the explanatory analysis of the scientific and political assumptions and theories regarding the nature of irrigation (as a synoptic of technology, institutions, people, land, crops, climate and water interacting with society and landscapes at different scales) that in turn makes sense of framings of irrigation environmental/technological knowledges (Blaikie, 1999; Forsyth, 2008; Peterson, 2000).

[2] The majority of the world's irrigation will remain under surface irrigation, particularly in a low carbon, expensive and intermittent-energy world.

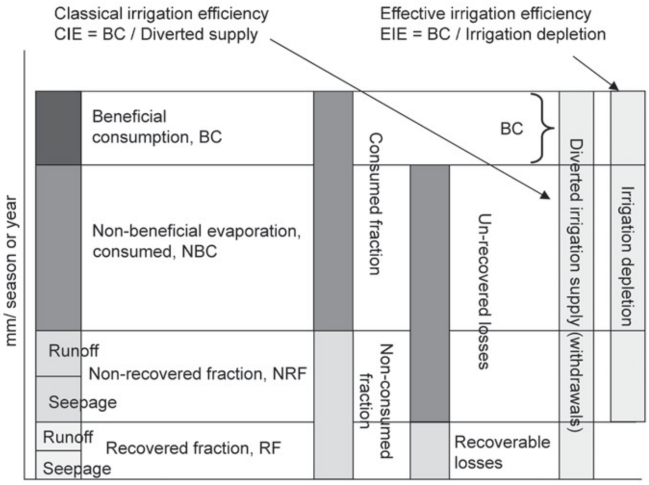

Fig. 1. Defining irrigation fractions and efficiencies.

recaptured usefully). In the second paradigm, termed 'socialised localised irrigation efficiency' (SLIE), Classical irrigation efficiency (CIE) is used as the ratio of beneficial evaporation of a crop (numerator) to the total inputs (or withdrawals) of irrigation water (denominator).

Allied closely with the basin accounting purpose of EIE, is the view that the magnitude of 'fractions' gives the required information on total water use or consumption within a system or river basin (Willardson et al., 1994; Perry, 2007; Jensen, 2007; Foster and Perry, 2010). Technically, the four fractions[3] as descriptions of flows in and out of an irrigation system are teleologically neutral and as be combined in different ways for understanding basin-allocation-irrigation efficiency or for socialised-localised irrigation efficiency. However in this paper, I align fractions with the BAIE model following Perry (2007) who distinguishes fractions from classical irrigation efficiency (for example his footnote on page 10[4]) and because Perry argues that it is the size, volumetrically, of fractions as inflow/outflow components[5] (rather than fractions as ratios of beneficial consumption to total water withdrawn, consumed or depleted) that gives useful information on the water balance of the basin or "real water-resource savings"[6] (Foster and Perry, 2010). Because my paper seeks to revalidate classical efficiency, I also opt to keep to two main paradigms rather than splintering them into sub-types; for example Perry (2007) makes the distinction between a fractions approach and effective irrigation efficiency.[7]

2.2. Boundary and scales – nested and aggregated systems

Water scientists are concerned with a highly mobile resource that moves through scalar boundaries (Donohew, 2009) and yet is used and consumed within systems and sub-systems of interest (Table 1) producing externalities in other scales and at other locations. Errors and heated debates arise from locating a concept intended for one boundary in an alternative boundary, or from applying one 'bounded' concept across all boundaries (see also Burt, 1999). For example, 'fractions' might be best applied to a unitary river basin rather than to single irrigation systems with complex canal networks and hierarchies.

As well as moving laterally across boundaries, water also moves vertically, lost to the surface and becoming a gain to groundwater or vice versa when capillary action waters crops. Discontinuous and irregular rainfall events complicate calculations. Furthermore connected with these boundaries (and boundary disputes) are disciplinary fields and stakeholder groups. As Table 1 indicates, moving from the micro to the macro, water and water distribution shifts from being the concern of the crop agronomist to the farmer to the irrigation engineer to the political scientist to the politician.

Within one scale, for example the irrigation system, water flows along particular paths; it is constantly dividing within a supply network and recombining in soil, aquifers and drains. Whether water is locally lost and recaptured again within the vicinity or further away in the basin depends on the fine details of this pathway architecture. In this way, irrigation systems can be viewed as hierarchically nested 'units' defined by water division and recombination within and between scales. The many units and boundaries also explain the inevitable political tensions that come from attempts at honest communication across boundaries in complex systems. As explained in Section 3, opportunities arise within the scalar level to divide water at a boundary between units establishing not only the proportions for the units but also distribution of the remainder flow for the hierarchical level below. Flow bifurcation, hitherto poorly recognised in the irrigation efficiency debate, defines the 'localised' role of classical irrigation efficiency.

Boundaries also establish vexing questions over ownership of water at different points along the pathway of water from withdrawal to the four main fractions. Thus while the beneficial consumption fraction belongs to the farmer with the appropriate legal water right, it is less clear to whom the non-recoverable and recoverable losses belong. On the one hand if a farmer has these fractions already specified in his/her water right to account for losses in distribution, maintains the drains on his or her land, and invests in minimising those losses, then he/she might claim the ensuing 'saved' water for consumption on his or her farm (Heaney et al., 2006) particularly via carry-over to another year if storage is possible (Young and McColl, 2003). In Tanzania water rights are issued with the specific instruction that unused water must be returned to the watercourse implying that drain water belongs to the state. Yet this does not work with the grain; farmers have little concern for their exiting drainage water and do not actively managed drains.

Analysing the efficiency debate via communication across these boundaries offers useful insights. While scientists might agree that classical irrigation efficiency is not a computation to understand water balances at the basin level, it is less obvious why BAIE supporters refrain from sanctioning the application of classical irrigation efficiency to understanding the performance of irrigation and intra-system levels beyond its initial design function. While I share concerns that CIE is poorly or incorrectly used to characterise irrigation systems, its information function, if the measure is derived carefully, has validity at the system level.

Plus there is currently no discussion or agreement on how we approach the question of aggregation and disaggregation of river

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[3] The four fractions in Fig. 1 are beneficial consumption, BC; non-beneficial consumed evaporation, NBC; non-recovered fraction, NRF; and recovered fraction, RF.

[4] The footnote reads: "In Egypt, it makes [. . .] very little sense to improve classical efficiency in upper Egypt because all return flows from that area are recovered downstream. This situation is self-evident once the descriptive "fractions" approach is applied, but entirely masked by the implicit "goodness" of improving "efficiency"."

[5] At the bottom of page 9, Perry (2007) uses the word 'components', though in the previous paragraph implies that fractions are synonymous with ratios: "This series of papers recommended using ratios or fractions to define water use so as to better consider impacts of return flows . . ."

[6] Foster and Perry (2010; page 294): "Real water-resource savings, which result in more water being available for other users (including environmental flows) and or for replenishing depleted aquifer storage, can only be achieved by reducing the size of the consumed fractions and or the non-consumed non-recoverable fraction . . ."

[7] Furthermore, with the scope of this paper in mind, I do not wish to debate here the differences between water consumption and water depletion; suffice to say I have added the NR fraction to BC and NBC to define irrigation depletion, while BC + NBC defines irrigation consumption.

Table 1
Boundaries within basin and irrigated water systems.

Approximate scale	Direction/plane	Boundary	Level	Debate/competition	Stakeholder/discipline
<0.1 m	Vertical	Transpiration/evaporation	Intra-system	Consumptive/ Non-beneficial/beneficial use	Crop biologist Agronomist
0.1–1 m 1–100 m	Vertical	Infiltration: surface to sub-surface Root-zone to water table Root-zone to aquifer Water table to root-zone			Soils agronomist Farmer/irrigator Farm manager
10–1000 m	Lateral	Farmers neighbouring other farmers. Fields neighbouring fields.		Equity within irrigation systems	Farmer Water user assoc.
100–10000 m	Lateral	Top end tertiary and secondary systems to tail end tertiary and secondary systems			Engineer Social scientists Researcher System manager
>10–100 km	Lateral	Rivers to irrigation systems Irrigation systems to wetlands/towns	System	Freshwater biodiversity Inter-sectoral allocation	Basin officer Water accountant
>10–1000 km	Lateral	Irrigation systems to other irrigation systems or other sectors	Basin	Inter-sectoral allocation	Economist Politician Donor

basins (Lankford, 2006) – how we construct a mental model of 'irrigation within the basin'. Thus in this issue, Karimov et al. (submitted for publication) seek to raise performance of the basin by taking a fractions point of view of the whole irrigation sector. I take this to be an 'aggregated' view of irrigation. In my view we should disaggregate the basin, taking each irrigation system individually and internally, spatially and seasonally. By addressing particular problems of each system at different times of the year it would be possible to identify the achievable interventions that might induce the greatest consumption or withdrawal 'savings' at a satisfactory cost.

2.3. Sequencing and logic

The contribution of effective efficiency and fractions has been to distinguish between system (project) efficiency and basin efficiency (Haie and Keller, 2008). Thus it is possible to recognise that losses to a project may be recaptured by basin. However, EIE and fractions scientists argue that increases in classical efficiency lead to more water being consumed from the project and basin because; (a) within an efficient system more water is consumed via crop transpiration (Ward and Pulido-Velázquez, 2008[8]; Haie and Keller, 2008), and (b) the area under command is extended if farmers or project managers have used 'saved' water from elsewhere in their system. It is these outcomes, if correct, that mean raising efficiency does not free up water for other uses.

Yet several steps in this sequence of logic have been assumed or consolidated. Other alternatives are possible. To assist with this analysis, Fig. 2 shows nine cases of proportions of the four fractions introduced in Fig. 1. In Case A, the four fractions are equal in proportion. In Cases B to E each of the fractions change with one dominating the other three. Cases F to I are additional possibilities, discussed below. Although missing from this figure (for the sake of clarity) are other combinations, this suggests that the relative amounts of each fraction may considerably change.

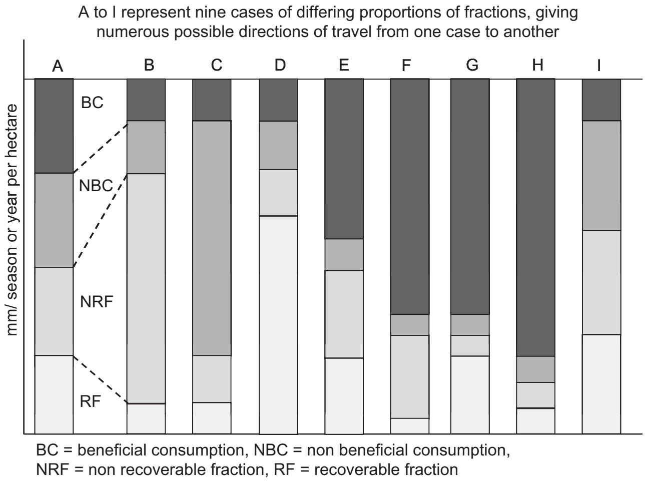

Fig. 2. Options for changes in magnitudes of fractions.

In the light of Fig. 2, caution should be applied to the first assumption of the switch from recoverable losses to beneficial transpiration under higher efficiency. While this may be the case, to make this assumption and policy inferences would require the majority of the world's irrigation systems to be experiencing recoverable losses that switch to beneficial transpiration under an efficiency improvement programme (Case A moves to Case F, or Case D to Case A). While this may partly be true in an (yet unknown) proportion of the world's irrigated areas, the assumption ignores the route that water lost via both non-recoverable losses and non-beneficial evaporation from irrigation systems switches to beneficial transpiration under conditions of improved water control and scheduling (Case A moves to Case G). While we have not spent sufficient effort on characterising the world's irrigation to answer this definitively, improved water control and scheduling results in more even applications of water within field and crops that are healthier in root and leaf development. This means that for a given irrigation cycle, water spends less time evaporating from open soil and more via transpiration (Case A moves to Case F). Yield is boosted for the same [BC + NBC] consumption, and possibly even less. As I suggest in Section 3 (also see Lankford, 2006), the three 'loss' fractions are coupled and as a consequence, an effective irrigation improvement programme results brings down all three (Case A moving to Case H). On the other hand, in systems in a state of poor management, all three 'loss' fractions may be higher as in Case I.

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[8] When I put to Frank Ward in an email the question; "My understanding is that you have assumed a larger area under drip and a larger ET under drip?", he replied (dated Thursday, December 11, 2008 12:41 AM) "Yes, our engineers tell us that for a given crop, ET is proportional to yield. So if a crop's yield is 20% higher under drip, then its ET is 20% higher".

Table 2
Multiple drivers of the rise and fall of irrigation efficiency.

Driver	Explanation
Incorrect design or poor assumptions in design	Subsequent system operation turns out to be very different from original design expectations (see Lankford and Gowing, 1996)
Changes in design and technology	Second approximations by farmers or purposive rehabilitation by donors, NGOs and farmers
Changes in irrigation operation	Failure to fix or maintain equipment or staff gate-keeping or to deal with unsanctioned turnouts can lead to changing flows to command area served. Ageing equipment leads to poor distribution and possible eventual abandonment
Price change	Varying prices for market goods, land, labour, water, electricity, energy, inputs, technology and soil management change farmers' perceptions on value of water relative to these inputs
New or use of storage facility	Changes to storage provide options and incentives to withhold water for timely use, crop ripening and deficit irrigation
Drought and or dry season	Shortage of rainfall intra- and inter-annually drives reduction in supply and alters practices to accommodate and match this
Seasonal or annual contraction from water abundance	After several years of good rain, a return to 'normal rain' leading to a probable contraction in area. Decreasing water table depths diminish water availability. Upstream developments reduce supply. All of these can drive new practices within a system
Rainfall event	The incidence of appreciable rain on a medium to large-scale system disrupts planned irrigation schedules during the event and afterwards; choosing when and where to irrigate as all soils in the command area are drying at the same rate down to wilting point
Extension in area	Farmers change practices driven by seeking larger command area from same water withdrawals
Fixed command area	Changes in four fractions within a fixed command area possibly lead to allocatable water at the headworks or changes in equity
Reduction in area/land use change	Loss of land via waterlogging, urbanisation, salinisation and absentee farmers might force/encourage adoption of new irrigation and water control practices
Incidence of conflict	Theft of water or hidden installations for unsanctioned withdrawals alter ratios of water to land. Perceptions of farmers holding on to water are problematic and need attention
Change in management (WUA)	Via new leadership or institutional agreements, fresh attempts at better scheduling, canal cleaning, in-field control
Change in water right	Reduction or increase in water right/licence imposed for a variety of reasons
Crop change	New markets drive crop diversification giving either reduced evapotranspiration intensities or different cropping patterns with subsequent seasonal changes to water distribution and depletion
Quality of crops	Improved prices for higher quality produce, or uniform crop ripening, drive changes in water control
Soil property change	Soil settlement or cracking or the installation of drainage can lead to changes in infiltration and runoff leading to shifts in the four fractions. Drain pipes blocked with silt also alter water movement
Salinisation and waterlogging	Seeking improved water control to reduce or increase the dose per irrigation alters efficiency
Change in farming system	Precision agriculture/horticulture (as an example) might influence the adoption of drip if row planting is enabled by new equipment

In the second assumption on areal growth, a 'control' has been omitted. For an increase in irrigation efficiency to lead to an increase in command area, scientists must be confident that this will not be controlled for by a reduction in withdrawal at the headworks. The circumstances in which we take this lack of control for granted are when its omission is entirely representative of the world's irrigation systems or where efficiency is always placed alongside allocation of the 'saved' water to another user – both questionable generalisations. With regards to the latter point, and as I make clear in this paper, we should also see efficiency as an issue for local users within their system's context. They may be facing, inter alia, a drought or growth of upstream demand; a reduction in water right; changes in crop type; or conflicts over differences in supply between top and tail-enders (Section 2.5 and Table 2).

2.4. *The purpose of efficiency; the connection to water allocation and productivity*

A number of writers have specified that the paradigm for understanding effective efficiency determines policy for dealing with water allocation in the face of increasing scarcity (Keller and Keller, 1995; Haie and Keller, 2008; Perry et al., 2009). Associated discussions (Molden et al., 2010) have pointed to the 'four primary ways of raising water productivity'; (a) increasing the productivity per unit of ET; (b) minimising non-beneficial depletion by reducing pollution and flows to sinks; (c) reusing return and drainage flows; and (d) reallocating water from lower value to higher value uses within the basin. The argument that ties allocation and productivity together is that 'real water savings' promulgate a reduction in consumption thus; (a) pushing up productivity (where the denominator of volume consumed decreases) and (b) freeing up 'real' water for allocation. On the other hand, it is proposed, 'paper water savings' are associated with technologies that do not reduce consumption and therefore cannot boost productivity or be employed for water allocation purposes.

However, seeking savings for allocation is not the only purpose for engaging with efficiency. In fact, there are five premises for employing classical efficiency. First, classical efficiency is recursively connected to water productivity via the 'adeptness' of irrigation; gaining control over water volumes and timings for responding to where and when water is required. This means a greater proportion of withdrawn water makes its way to beneficial consumption. This more precise timely watering made possible by (indeed defined by) efficient irrigation which raises productivity through; timely irrigation scheduling within a rotational/divisional/catenating supply (see Section 3.3); the coordination of other crop and farm inputs (see the point below); and control over cropping calendars by narrowing the progress of planting as a function of water arrival and completion.

Adept irrigation has another dimension to it. The 'paper versus real savings' distinction is only an effective argument if the different fractions are malleable individually and distinctly – yet I argue in Section 3.4 the fractions are coupled together. If coupling exists, paper savings would indirectly lead to real water savings.

The second purpose of classical irrigation efficiency (also related to productivity) is to gain control over and therefore reduce other inputs associated with water volumes and timing – notable is the energy used to source and reticulate the gross withdrawal volume from surface and groundwater sources for irrigation, see this issue (Karimi et al., 2011) for similar points made. Other inputs and costs associated with water withdrawals include agrochemicals and labour.

Third, classical irrigation efficiencies are employed in designing and sizing canals and intakes for water withdrawals and reticulation. Perry (2007) and others acknowledge this purpose. In this regard the difficulty that effective irrigation faces [without it being modified back into classical efficiency as Haie and Keller (2008) propose] is that in aiming to account for consumption only (while addressing water quality and other values) would require new design methodologies and protocols to be established. There is no sign these are being developed for irrigation engineers.

The fourth purpose is a human one and relates to ideas of a socialised model of efficiency while addressing equity; that local losses produce and shape farmers' perceptions of their neighbours' water use. In a bifurcating model of irrigation systems where water flows are either being split, rotated or catenated respectively, recoverable losses should not be seen as water 'destined' for the basin but as water for one's neighbour. In such cases, efficiency helps to understand these differences in water volumes and timings, or in other words, to mediate conflicts. Yet losses and efficiency (rather than access to, or volume of, supply) are often pretermitted in this because the factors affecting efficiency are hidden, dispersed and multiple making efficiency ambiguous and efficiency gains elusive. However to deduce that efficiency and savings are not of interest to farmers (Foster and Perry, 2010) speaks more about a failure to engage with farmers than about efficiency's arbitral value to farmers keenly aware of their place in a queue of a limited water supply.

The fifth premise for adopting CIE regards the policy implications of how a basin and its irrigation sector are aggregated or disaggregated for the intention of making savings for water allocation. Following the point raised in Section 2.2, classical efficiency could play a part in water allocation if its merit at the system level allows allocation scientists to knit together bottom-up farmer centred savings with basin perspectives of total consumption.

In discussing how the two paradigms of efficiency speak to water allocation, I believe substantiation and evidence to be as important as the theory. To make my point, I take an example of each paradigm and relate them to Fig. 2. Perhaps the most egregious example of classical efficiency improvements employed incorrectly as a basis for water reallocation relates to a World Bank project in Tanzania, funded from 1995 to 2005, termed the 'River Basin Management and Smallholder Irrigation Improvement Project' (RBMSIIP) (World Bank, 2010). As I have written on this elsewhere (Lankford et al., 2009; RIPARWIN, 2006) I briefly explain that RBMSIIP was funded on the premise the project could raise efficiency from 15% to 30%, allowing substantial reallocation of water,[9] as this quote from page 42 of the Appraisal Report (World Bank, 1996) explains: "*In order to illustrate this effect, the 'savings' in water which result from the improvement of some 7,000 ha of traditional irrigated area under the project (this includes both basins) are valued using their capacity to generate electricity in the downstream turbines. An average 'in the field' requirement of 8,000 m^3 of water, for one ha of rice production, implies withdrawal of 53,300 m^3 from the river, with an irrigation efficiency of 15 percent. Following improvements in irrigation infrastructure and an increase in irrigation efficiency to 30 percent, the withdrawal requirement from the river drops to 26,700 m^3 per hectare. This releases some 26,700 m^3 for every hectare of improved irrigation, to be used for hydropower generation downstream. For this exercise, the water is valued at 5 US cents per m^3, the valuation for residential electricity use (34 percent of all electricity use, and intermediate point between the two alternate values).*

Noting the incongruence of 5.3 m of water depth being withdrawn for every 0.8 m of evapotranspiration, shifting from case B, C or D (I give various options since the fractions of the 'losses' are not specified) to either F or H in Fig. 2 would have to apply for this type of construct to have validity – clearly a misleading basis for a water development project, and particularly so for case D where water is/was being recovered.

In the 'fractions' camp we might also see unsubstantiated examples where locally lost water is believed to be captured by the basin without costs, externalities or options for managing water: "*... one of the World Bank's Chief advisers on water, Stephen Foster of the British Geological Survey is horrified by the idea that making irrigation more efficient will free water for other uses "It has the makings of a very dangerous myth", he says. There is, he adds, a horrible flaw in the argument. Most of the water being "saved" is never truly wasted in the first place. Some, it is true, is lost to evaporation. But most – the water that seeps underground from fields and canals – eventually finds its way to nature's underground water reservoirs, from which millions of farmers subsequently pump water to supplement river water for irrigation*" (Pearce, 2004).

This hydrological scenario has most of the water not beneficially consumed by crops finding its way to underground stores, recycled by millions of farmers. Utilising Fig. 2, Case D (relative to Case H) dominates world irrigation for Foster's vision to be true – a myth constructed equal to the myth deconstructed. Whether both savings and allocation can be achieved by coherent changes in water policy – and thus be assessed under allocative efficiency – is open to question. Huffaker and Whittlesey (2000) in their study of measures to allocate water on the basis of irrigation efficiency improvements believed that conditions had to be highly specific for this to succeed.

2.5. Shifts in efficiency and context

Shifts in irrigation losses and efficiency offer fertile ground for making or correcting errors in thinking. For example the fractions/EIE literature is rightly concerned about the questionable belief that a move to a higher efficiency makes water available for other sectors. Yet this literature in turn erroneously sees that classic efficiency is used in only two ways; correctly employed in design and incorrectly employed alongside allocation. This view precludes the dynamic circumstances that irrigation experiences, where, accordingly, classical irrigation efficiency changes and gains meaning. Irrigation systems adjust in constitution and specification reflecting internal and wider forces, so for example, irrigation schemes evolve from being 'designed', to 'commissioned' to 'in use' to 'aged' to 'rehabilitated'. They can be part modernised or wholly transferred to smallholders or sold to the private sector. As Table 2 shows, the variety of change options is large, with each system facing unique combinations of drivers acting in unison or tension.

To negate CIE requires us to believe it is static prior to an allocation intervention and that it gains its significance from attempts at allocation and that net consumption from the basin increases when efficiency increases (undoing allocation). Although in Table 2 the outcome for each driver is by no means certain or unidirectional (efficiency may increase or decrease and net consumption from the basin may increase or decrease), it is not always the case that classical irrigation efficiency is in lockstep with water allocation.

Taking this and the previous sub-section together, I argue that efficiency and the 'saving of water' has multiple meanings at different scales for different time periods for diverse stakeholders in complex trajectories of short and long-term change. This is why I refute the assertion made by Foster and Perry (2010, p. 294) "Indeed, the reason for a farmer changing irrigation technology is rarely to save water, but more often to seek other (to him) important benefits". They then specify productivity (via high value

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[9] Similarly the Japanese ODA body, JICA, working in Tanzania in the nineties also believed smallholders to be inefficient and that for example, lining smallholder canals upstream of the Lower Moshi Irrigation Scheme would bring significantly more water to this scheme.

crops), energy and labour. While I agree these are reasons for saving water, this is a view that sees 'saving' in context with allocation, and that farmers are not interested in saving water other than the reasons given by Foster and Perry. My experience is that farmers are interested in saving water as part of managing water – or when *compelled to save water* by circumstances beyond their control (e.g. a drought). This opens up grounds for research on farmer perspectives on efficiency – in particular taking a socialised systems approach where farmers might be encouraged to see that gains to their individual performance emanate from not only from them but from improvements to the whole irrigation system. Given the right circumstances for promoting dialogue (Magombeyi et al., 2008), downstream irrigators expressing concern at the 'waste of upstream neighbours', very much wish to control water volumes in a more timely or equitable fashion.

2.6. *Implications of judging percentages*

The categorisation of three main types of irrigation technologies with attendant ranges of efficiency (surface, less than 40%; sprinkler, 60–70%; drip, 80–95%) leads irrigation professionals to employ efficiency figures expressed out of 100 as an 'absolute' index to adduce higher performance can be obtained by switching technologies. While this categorisation may apply in broad terms, it falsely offers a simplified sense of performance analysis as well as obviating, I believe, the need to conduct better field research. More importantly, although a lack of empirically fed advisory guidelines might be one explanation for a failure to be more critical (or indeed more informal) in judging efficiency, the absolute expression of efficiency in 'per cent' terms plays to the basin-allocation arguments of eliminating classical efficiency. As explained in Lankford (2006), a pejorative element arises when we use measures expressed out of an impossible target of 100%. Yet to employ classical irrigation efficiency with credibility requires measures in keeping with the localised scale that CIE addresses. Lankford (2006) suggests a comparison of local systems to derive attainable efficiency[10] – the most effective being a ratio of the water consumption of water-short tailend users to the water consumption of water-rich topenders. An attainable irrigation calculation keeps the frame of reference between situations 'a' and 'b' and resets the denominator making interpretation of results locally realistic and useful. Willardson (1972), problematising efficiency, first used term 'attainable irrigation' understanding that efficiency figures are relatively meaningless when set against an unattainable target of only meeting CWR. In addition, 'irrigation sagacity' proposed by Solomon and Burt (1999) suggests caution when judging the performance of irrigation systems.

2.7. *Agreeing terminologies*

The debate on irrigation efficiency revolves to some extent around attempts to impose definitions (see Halsema and Vincent, in this issue for further discussion on this). This is one response to both lax use of the many terms in circulation and the complicating nested or fractal nature of irrigation systems. For example the agreement by the journal Irrigation and Drainage (Perry, 2007) to adopt a fixed terminology on behalf of the International Commission on Irrigation and Drainage (ICID) reflects significant concerns about lax use of terms – exemplified in the title of Perry's paper (2007) "Efficient irrigation; inefficient communication; flawed recommendations".

Terminology discrepancies are a real concern. Peer-reviewed and grey literature abounds with terms used loosely and interchangeably, or terms are introduced without definition, for example within one irrigation policy document, the Government of Tanzania use 'water use efficiency', 'water use inefficiency', 'irrigation efficiency', and 'water utilisation efficiency' (GoT, 2009, pp. 8, 17, 24, 29 respectively). 'Water use efficiency' (Howell, 2001) is commonly misused to mean irrigation efficiency (see for example Belder et al., 2007). Within the short life-history of the fractions concept, one sees diversity emerging. IWMI have developed their own versions (see Karimov et al., submitted for publication as have Haie and Keller, 2008, and Pereira et al., in this issue). In the analyses by Bos et al. (2009), other subtle changes (e.g. depleted rather than consumed fraction) to terminology are utilised. Haie and Keller (2008) urge the abandonment of classical efficiency as a term but yet question the use of the term 'fractions'. Earlier IWMI papers (Seckler, 1996) also sought to bring closure to definitions regarding water management. Recent papers (Foster and Perry, 2010; Perry et al., 2009) and future papers[11] also aim to resolve discrepancies in definition.

To seek to finalise terms within an unfinished on-going debate is questionable. Furthermore, because irrigation is nested within larger systems linked intimately to labour, land and energy, and to human perceptions of water access, an insistence on universal terms may ultimately be frustrating. Exhorting scientists to agree terms on the basis of hydrology (Perry, 2007) and soil–water (Foster and Perry, 2010) fails to recognise the 'systems' and social nature of irrigation at different scales, particularly the intra-irrigation bifurcating fractures that bring out the role of basin-recoverable losses in causing local differences in access and supply (see Section 3.3).

2.8. *Insufficient evidence*

Running throughout this debate is a paucity of quantitative data drawn from accurately conducted studies of irrigation performance. Judgement of performance requires water flows over time and space to be traced using multiple methods also exploring farmer expressions of efficiency rather than relying on single methods, e.g. canal flow measurements. Instead papers often offer conceptual arguments, or rely on a modelling approach or on survey questionnaires where verification and standardisation of the respondent's methods is not available [as happened with the results collated by Bos and Nugteren (1990)]. Where measurements have been undertaken, papers tend to deal with one scale (the field level) or agronomic water use efficiency (Payero et al., 2009). These types of papers (modelling, questionnaire or agronomic) lack the necessary substantiation to make compelling arguments regarding the dynamics of irrigation efficiency.

For example in the literature on irrigation in Tanzania, efficiency is defined in reports (Faraji and Masenza, 1992; RBMSIIP, 2001; Masija, 2001), yet no origin of the data is offered. Varela-Ortega and Sagardoy (2003) also reproduced figures on irrigation in Syria without evidence; "Basin irrigation is the predominant technique used in surface irrigation and most of the irrigated wheat and barley are irrigated by this method. Irrigation field efficiency is reportedly low, often around 40% in the old networks (50 years) and around 60% in the more recent ones (15 years)".

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[10] Attainable irrigation efficiency (AIE) = 'target' irrigation depletion/'found' irrigation depletion. Where 'target' irrigation depletion represents realistic attainable figures by water-short irrigators in the area and, 'found' irrigation depletion represents local examples of water profligacy that result in non-reusable depletion. Target = 927 mm, tail-enders in Tanzania, 3–5 t/ha rice. Found = 1385 mm, top-enders in Tanzania 2–3 t/ha rice. Attainable efficiency = 927/1385 = 67% (Machibya, 2003).

[11] The journal Agricultural Water Management aims to publish a paper on terms it shall adopt in the editorial process. David Molden (pers. comm.) also intends to work further on terms.

2.9. *Inferring performance from technology type*

There exist confusions over modes of modernity in irrigation, with different types being strongly associated or even representing levels of waste. 'Traditional' implies considerable waste while 'modern' relates to reduction in waste: "*Even in the mainly urbanised Damascus basin, however, around 80 percent of available water is used in agriculture, with outdated irrigation methods wasting huge quantities of it. Across Syria as a whole, only 16 percent of farmers use modern irrigation systems, according to JICA's Mori.*" (IRIN, 2010). While this quote does not specify a definition of 'modern', further investigation makes clear that Syria defines modern technology as drip and sprinkler systems (Varela-Ortega and Sagardoy, 2003). That gravity systems in Syria constitute 95% by area reveals a further worrying fault in logic, picked up elsewhere in this paper; limited experiences on small areas of pressurised sprinkler and drip under private control are being proposed, at least in part, as the public solution to modernising large-scale gravity systems. This association is problematic given that gravity systems can be upgraded by other means (see FAO, 2007). Nevertheless, the political dimensions of associating technology with performance was captured by Kay (2001); '*Are these modern technologies as good as people say, or are they just another quick fix promoted by those who have a vested interest in selling the equipment? Are the traditional technologies being simply ignored because it is psychologically easier to invest in sprinkler and trickle irrigation that are regarded as* '*efficient and modern*' *whereas traditional methods are regarded as 'old and inefficient*'?

3. Irrigation efficiency science – factorials and fractions

In this section I cover four interrelated topics that allow me to question the basin-allocation (fractions/EIE) approach to efficiency and to propose that CIE can also be used as a deliberative, management and performance tool.

3.1. *The 'factorial' method of determining efficiency*

The common view that surface irrigation efficiency is low is a result of decades of reiteration that systems are less than 40% efficient (as an example see summary on page 1 of Seckler, 1996). Setting aside our inability to interpret this meaningfully (Section 2.6), while low efficiency is properly critiqued from a fractions point of view because of multiple re-use within the river basin, this assessment is 'classically' flawed because of micro-scale local re-use within the boundaries of an irrigation system. Classical irrigation efficiency is lumbered with a 'methods legacy' that fails to capture the totality of water use within irrigation systems. The method, applied as a set of assumptions during design to size canals and turnouts, multiplies different levels or tiers of irrigation systems together; i.e. the conveyance, distribution and field application efficiencies (Burman et al., 1983; Heermann et al., 1992; Merwe et al., 1997; Doorenbos and Pruitt, 1992). It is the multiplication of different levels together that gives me mathematical licence to term this 'factorial'. For example, a conveyance system efficiency (ec, 0.8) multiplied by a distribution system efficiency (ed, 0.6) times a field application efficiency (ea, 0.7) gives a total project efficiency of 34%; figures taken from Machibya (2003) for Kapunga Smallholder Scheme in Southern Tanzania.

Yet taking a factorial design methodology to devise a sampling methodology ('snapshot' measurements of flows to quantify volumetric losses between point X and point Y) leads to misrepresentations of whole system efficiency. It was this method of determining canal losses employed by Masenza (2000) to find remarkable improvements in efficiency in post-project monitoring by the World Bank (2007).

Regarding the sensitivity of the factorial method to errors, employing three or four tiers within a multiplication exaggerates the cumulative outcome of changes to the three figures. Returning to the Tanzanian example, a 0.1 fraction increase in each individual component ($0.9 \times 0.7 \times 0.8$, given here for the neighbouring Kapunga Irrigation Farm design) raises the total efficiency from 34% to 50% – a marked increase. On this basis alone, it is not surprising that the World Bank (2007) decreed for RBMSIIP that "Average irrigation efficiency for both basins increased to 27 percent at project closing, compared to the average of 15–20 percent before the project".

For system assessment, classical efficiency should not be determined by a single snapshot. Instead, because water seeps and migrates through the system over time, the measure should capture water over a broader area over a given time window. Even on a smaller diurnal or weekly time-scale, canals and fields empty and fill depending on upstream manipulations of gated controls, or because of the relative heights of canal and field water levels and the surrounding water table. As Machibya found during his PhD fieldwork (2003) on the Kapunga Irrigation Farm, canals gained water during tests as well as lost water at other times. A leak in a canal passing a field is at times an unsanctioned contribution to that field's water supply. Efficiency is highly dynamic in time and space and arises out of many small alterations to operation and maintenance. If this is not recognised then sampling surveys are invariably under-designed with the consequence that the factorial method over-emphasises any errors in efficiency calculations.

A suitable methodology should recognise that system efficiencies are in a constant state of flux; changing over different time frames – daily, weekly, monthly, seasonally and yearly – and changing from place to place. These arise because of the operational mismatch between supply and demand where both constantly vary. Supply changes relative to design or relative to averages because of surges in river flows, alterations to turnouts, or because runoff from rainfall events contribute to canal flow or because groundwater seepage adds to inflows. Demand changes because of shifting growth patterns arising from the planting and harvesting of seasonal and perennial crops, or because farmers hold onto water, storing it in bunds to a greater depth than necessary, or because soil properties change over time, as settlement or cracks develop. Losses occur through entirely commonplace but controllable switching – for example at the start of night-time a canal's flow might go to waste to the drain as no gate-keeper or farmer is present to direct it.

With regards to the last point made, the major reason weeds and silt are less than desirable in canals is not because they raise losses via seepage or evapotranspiration but because they change the stage–discharge relationship of a canal. For a given height of water, the discharge is lower, and through frictional head-loss the peak discharge takes longer to arrive at and decline from, effectively promoting un-monitored operational volumetric losses and inefficiencies at the start and end of the day or farmer 'turn'. Yet, these losses, not commonly measured with the snapshot methodology, may be or may not be part of useful soil wetting and crop transpiration within the same irrigation system.

The configuration of an irrigation system's canals and drains will also dictate to some extent the immediacy and ease with which field losses are recaptured either within an irrigation system's original command area, or via areal extension at the tailend, or via the watering of systems unconnected to the 'donating' system, or move to drains beyond the reach of further beneficial use either locally or within the catchment (a point picked up in Fig. 6).

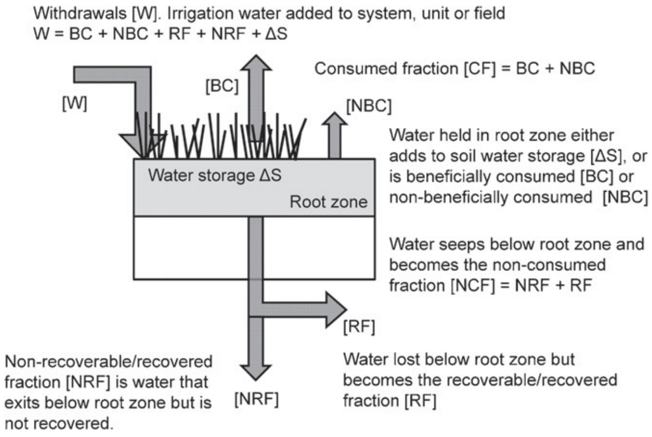

Fig. 3. The block model of BAIE.

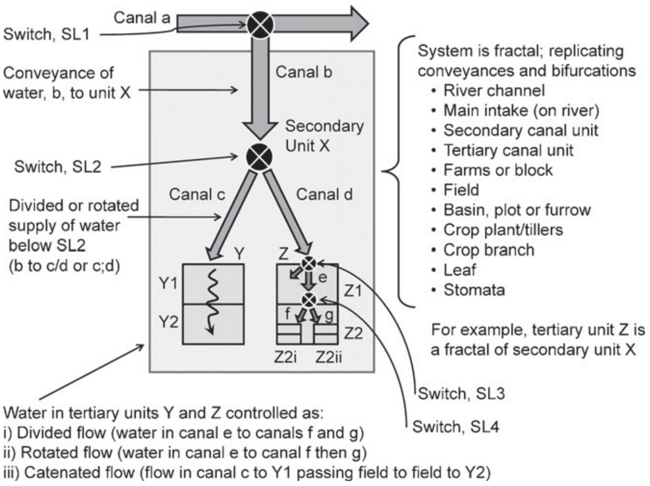

Fig. 4. The bifurcation model of SLIE (plan view).

3.2. *Our mental model of irrigation systems: fractures (and fractals)*

In this section, I show how the basin-allocation-efficiency and socialised localised (classical) efficiency paradigms adopt different partitioning models of water flow in an irrigation system. In doing so, I contrast the 'fractal' nature of the two models – how a water demand unit is nested; that is replicated higher up or lower down within hierarchical canal systems.

3.2.1. *The 'block' model of irrigation systems for BAIE*

In articles that extend over more than 15 years (Keller and Keller, 1995; Clemmens and Burt, 1997; Foster and Perry, 2010), Fig. 3 has been the core conceptual model of inflows and outflows to and from an irrigation system. It shows a box or 'block' representing an irrigation system. The block has a main input flow termed W, (withdrawals) and four exit pathways or fractions (BC, NBC, RF, NRF), plus a change in internally stored water content ΔS. This model with its logic of mass continuity is internally valid because the 'input' flow and four 'exits' flows mutually affect and balance each other. For a fixed withdrawal (input) volume, if consumption rises then recoverable losses and allocatable volumes diminish. The block is conceptually located in a white space implicated to be the river basin. It is this flow mass-continuity plus the definition and location of recoverable flows that connects this model to the concerns and science of basin water accounting. Here, recoverable flows move to or 'belong' to the river basin and, as a fraction within withdrawal (W), are computationally neutral from the basin's point of view.[12]

While hydrologically sound for block-type irrigation systems where water can be applied quickly (e.g. individual centre-pivot systems), it is possible to question the block model. This can be done by conceiving irrigation units as having intra and inter-block divisions and pathways of water and as sitting alongside, or upstream or downstream, of other units – in a neighbourhood mosaic. This configuration describes hierarchical networked canal systems supplying farmers and fields. As I explain next, if irrigation systems are seen as bifurcating/rotating/catenating blocks sitting in a neighbourhood of blocks rather than a single block sitting in a basin, then classical efficiency keeps its managerial, assessment and performance significance.

3.2.2. *The bifurcating model of irrigation systems for SLIE*

Irrigation involves the control of water; the apportionment, via division, of a bulk water supply through pipes, canals and switch points to individual farmers, fields and plants in a timely fashion. Other infrastructure and physical aids (such as the depth of the water table, gradients and drainage equipment) may assist. With the exception of when water is recombining in an aquifer or water table, it is vital to recognise that water apportionment involves the bifurcation of the main supply to smaller flow rates and volumes sized for sub-canals, farmers, fields, furrows and plants. For example main canal water can split down two secondary canals. In another case, water might either move laterally along a field or seep vertically through the soil profile below the root-zone. It is this act of bifurcation (or potential to bifurcate established by irrigation/field/soil architecture) that defines the 'fractures' found in irrigation systems (and in the title of this paper), offering the starting point for the three means to share and schedule water; by division, by rotation and by catenation (Fig. 5 defines these). Equally, it is this flow fracturing, this act of division or bifurcation, that defines the difference of this model to that of the 'block' model where no internal split is presented. Division creates irrigation units in neighbourly arrays that share a common supply so that losses on one side of the bifurcation act as a true unrecovered losses to the neighbouring unit on the other side of the bifurcation (rather than as cost-less recoverable losses to the basin). The consequences of water losses in a bifurcating model for irrigation performance are explained in below (in connection with 'timing' points made in Section 3.3).

The fractured bifurcating nature of irrigation systems is demonstrated in Fig. 4 through the sequence of switch points for each tier. Switch point (SL1) provides water for a secondary unit of demand X. Within secondary unit X, division point SL2 splits water in two proportions to canals 'c' to 'd' simultaneously. However also at SL2, the whole flow of canal 'b' could be rotated between 'c' and 'd' to feed first Y then Z. Within tertiary unit Y, water can catenate (flowing overland field to field) by moving from subunit Y1 to subunit Y2. In tertiary unit Z, water has three options for apportionment; it can either divide at SL3 in a continuous flow between Z1 and Z2, rotate between them (Z1 then Z2) or catenate from Z1 to Z2. Figs. 5 and 6 can be studied to give further insights as to how divisions, rotations and catenas determine the significance of losses – explained in Section 3.4. Significantly it is the multiple hierarchies and number of switch points that offer considerable scope for managing well or poorly the control of water. Via a culmination of incorrect designs or operational settings, inequity of supply is subtly magnified.

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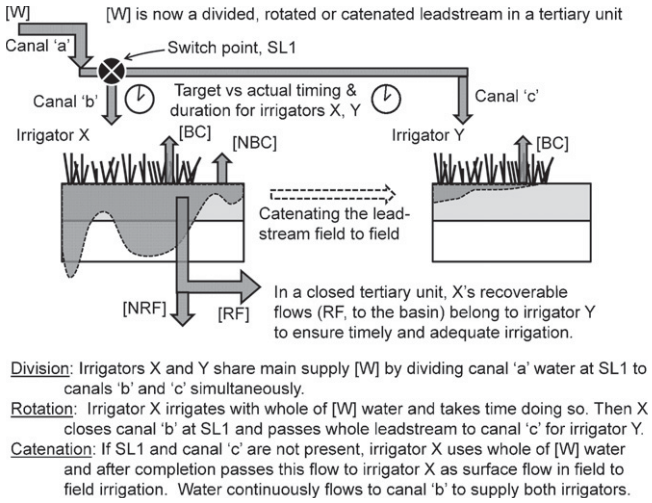
[12] *"However, (. . .) from the perspective of a groundwater body or hydrological basin, the situation is very different, since a (variable) part of the farmers 'loss' is returned to underlying groundwater and/or to downstream surface water (. . .), and thus is not 'lost' with respect to other users and uses"*. Foster and Perry (2010, page 292).



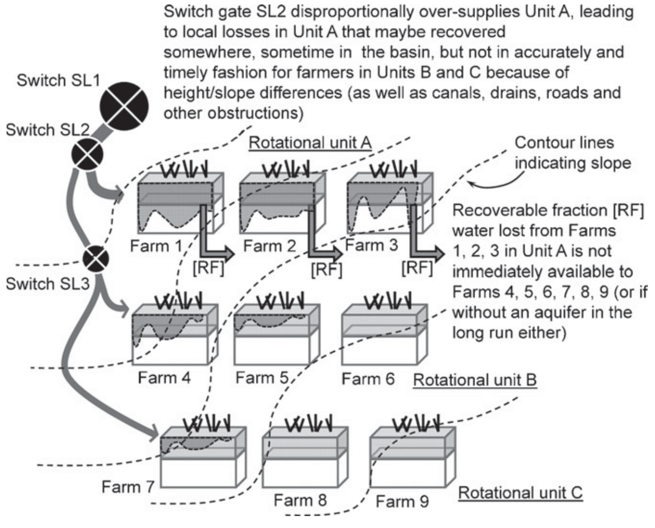
In a closed tertiary unit, X's recoverable flows (RF, to the basin) belong to irrigator Y to ensure timely and adequate irrigation.

Division: Irrigators X and Y share main supply [W] by dividing canal 'a' water at SL1 to canals 'b' and 'c' simultaneously.
Rotation: Irrigator X irrigates with whole of [W] water and takes time doing so. Then X closes canal 'b' at SL1 and passes whole leadstream to canal 'c' for irrigator Y.
Catenation: If SL1 and canal 'c' are not present, irrigator X uses whole of [W] water and after completion passes this flow to irrigator X as surface flow in field to field irrigation. Water continuously flows to canal 'b' to supply both irrigators.

Fig. 5. The bifurcation model of SLIE (section view).

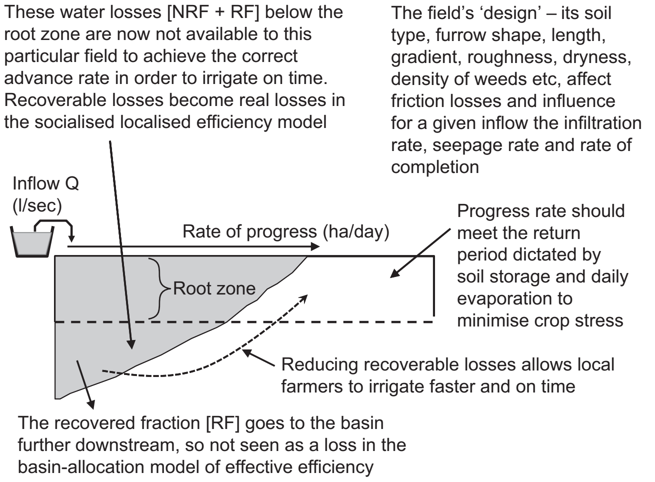
Critical to this bifurcation model are three provisos. First, water flows downhill under gravity and takes time to move through the landscape. Although the term 'recoverable losses' may be used, this only applies to a localised bifurcating model of project efficiency when the 'reused' fraction is reemployed in the system within a time frame useful for crop production at a cost profitable to do so – for example when drains become canals further downslope, or when utilising pumps to recycle water, or when a water table is raised to supply crops with capillary-fed water or later on in the season. What cannot be countenanced are other scenarios (Fig. 6): where a water loss from one field moves laterally to other fields that are effectively too distant from each other or on a similar contour line; where the travel time is too long for useful crop production; where the drainage route has by-passed locations where water might have usefully compensated for losses upstream; where recovery is prohibitively costly; and when water quality has degraded.

Under a second proviso, water entering a unit of demand (secondary or tertiary unit) is normally at or below a capped rate dictated by the original design or subsequent design alterations. Because of this 'control,' any water loss occurring in the command area being supplied cannot be compensated for by additional flow to the unit. This results in slower irrigation scheduling within the unit.


Switch gate SL2 disproportionally over-supplies Unit A, leading to local losses in Unit A that maybe recovered somewhere, sometime in the basin, but not in accurately and timely fashion for farmers in Units B and C because of height/slope differences (as well as canals, drains, roads and other obstructions)

Recoverable fraction [RF] water lost from Farms 1, 2, 3 in Unit A is not immediately available to Farms 4, 5, 6, 7, 8, 9 (or if without an aquifer in the long run either)

Fig. 6. Multiple bifurcations on an irrigation system.


These water losses [NRF + RF] below the root zone are now not available to this particular field to achieve the correct advance rate in order to irrigate on time. Recoverable losses become real losses in the socialised localised efficiency model

The field's 'design' – its soil type, furrow shape, length, gradient, roughness, dryness, density of weeds etc, affect friction losses and influence for a given inflow the infiltration rate, seepage rate and rate of completion

Progress rate should meet the return period dictated by soil storage and daily evaporation to minimise crop stress

Reducing recoverable losses allows local farmers to irrigate faster and on time

The recovered fraction [RF] goes to the basin further downstream, so not seen as a loss in the basin-allocation model of effective efficiency

Fig. 7. Relationship between recoverable losses and completion rate of irrigation.

In a third proviso, the influence of the original design assumptions in construction or rehabilitation in allowing for local losses (so that the remaining 'net' amount does not influence scheduling) has been superseded by the drivers outlined in Table 2. In other words, a considerable number of 'real world events' intervene to provide irrigation systems with greater or less water, or that favour one bifurcation over another, in contrast to the original design and operation intentions.

3.3. *Time, timing and durations*

Timing elements of irrigation distinguish the two efficiency paradigms. On the basis of time, timing and durations I question the limits of a basin-allocation-efficiency model that treats an irrigation system as a block partitioning a single seasonal volume of (say) 7500 m^3 into fractions. More meaningful for the management of those systems is a daily or weekly timeframe where timing of irrigation delivery is important because irrigation systems contain living plants that do not respond to irrigation beyond permanent wilting point. Timing of water delivery (Fig. 7) arises from two interrelated factors; friction head losses and physical water losses (NBC, NRF and RF) and can be captured in the equation: [(Net required dose of irrigation, mm depth) = (flow rate, l/s) × (time taken to irrigate, hours) × (classical efficiency, '*x*'%) × (0.36)/(completed area irrigated, hectares)] (see Lankford, 2006). A low classical efficiency reduces the ability to cycle on time. If a farmer irrigates for too long, the impact is not only on his or her productivity or where the recoverable fraction 'ends up' but on delays relayed to her neighbour sharing the same water supply.

In Fig. 4, the four tertiary units (Y1, Y2, Z1 and Z2) give a variety of combinations which determine how local water losses affect the secondary unit X as a whole. In one example, a 'carousel' is created by water rotating between the subunits Y1, Y2, Z1 and Z2. Water lost in unit Y1, yet not compensated for by an increase in flow at SL1 generates a slower rotation of water for all of Y1, Y2, Z1 and Z2. In another example, if canals 'c' and 'd' each create a discrete hierarchy, then the flow from SL2 is split and continuously flows to canals 'c' and 'd'. From here water can either cascade in series from Y1 to Y2, or water flows continuously between Y1 and Y2 or water moves in rotation from Z1 to Z2. In these cases, recoverable losses in unit Y are not recovered back to the switch 'SL2' to provide for water at Z and recoverable losses (to the basin) in unit Y1 generate a slower catenation of water to Y2.

In summary, efficient (in the classical sense) systems are those that contain the right proportion of water to irrigated area at each switch/bifurcation opportunity to ensure the next switch down

Table 3
Application of efficiency concepts.

Main paradigm →	Socialised-localised efficiency	Basin-allocation efficiency
Efficiency formulation →	CIE	EIE/Fractions
Purpose ↓		
Irrigation system design	√	××
Irrigation water and inputs management	√	××
Irrigator and group equity perspectives	√	××
Irrigation productivity management	√	(√)
Irrigation modelling and assessment	√	(√)
Basin modelling and assessment	××	√
Basin productivity	(√)	√
Basin management and allocation policy	(√)	√

Key: √ required for purpose; ×× not required for this purpose; (√) assists.

receives its correct volume of water allowing it in turn to divide at the next switch. If the supply meets the demand established by the daily evapotranspiration and soil water storage, then the rate of completion is maintained allowing the next irrigation dose to be scheduled on time.

3.4. Coupling of fractions

In an earlier paper (Lankford, 2006) I reasoned that the four fractions were coupled or linked – meaning that the quantity of one fraction cannot be altered without affecting another fraction. For example the greater the net crop water requirement, the greater the losses, and with greater recovered losses come greater unrecovered losses. Hence deficit irrigation, which reduces the crop water requirement dosage - predicated on good canal and field water control, can reduce the three types of losses. This inter-relationship will be highly specific to the conditions found on an irrigation system. Its implications are that paper and real savings are inter-linked and either one cannot be adjusted unilaterally.

4. Combining the models – a broader framework

In agreement with Haie and Keller (2008) the term 'efficiency' should be retained but unlike them, with specific reference to the habitation of irrigation systems by farmers and crops, this paper goes further and argues that 'classical irrigation efficiency' should be put to careful use. Recoverable as well as other types of non-productive losses matter locally and therefore the ratio of beneficial evapotranspiration to total water input has real meaning. More broadly, in a context where society is moving towards a water scarcity and equity era, ratios of benefits from effort (or outputs from input) will become more significant.

The objective of this paper is not to propose new or argue existing definitions but to adumbrate, through a revalidation of classical irrigation efficiency, a broader framework of the purposes and jurisdictions of the two main paradigms. This framework is provided briefly in Table 3, suggesting that CIE is used for four main purposes; for design; for the control of water scheduling to raise productivity; for co-ordinating other inputs; and to attend to farmers' perspectives about equity and timing. The basin allocation irrigation efficiency model (EIE/fractions) is more applicable to modelling of the basin particularly in connection with water allocation. Moreover, fractions terminology becomes a part of the overall map to navigate irrigation and basin efficiency and productivity, and has a central role in examining the impacts of improved water management on total consumption and allocation. Nevertheless, discounting the role that classical irrigation efficiency plays in basin management, allocation and productivity would be a mistake. To imagine allocation can be managed while being indifferent towards irrigation systems fractured into water rich top-enders and water poor tail-enders is to deny the social dimensions of irrigation and the role of classical irrigation efficiency in examining intra-sector apportionment.

5. Conclusions

The allure of irrigation efficiency as a single measure of system performance produces, in part, the doubts that irrigation scientists hold with it. Notionally simple, it is highly prone to capture by groups that engage with irrigation, feeding through variously to public and scientist/engineer understandings, and policies and practices regarding irrigation and water allocation. It can, without doubt, be misunderstood. Donors, advisers and irrigation engineers often ignore that irrigation systems sit, nested, within larger systems of recapture and reuse. Thus a 'loss' from one unit within the hierarchy should be parenthesised, qualified and quantified. Raising irrigation efficiency can lead to increased consumption from the basin if the consumed fraction increases relative to the recovered fraction. That it needs an improved method of accounts as sought by Foster and Perry (2010) also is true (although the nature of those accounts has yet to be determined). Moreover, to infer efficiency by referring to a system's provenance as 'traditional' or 'modern' without offering metrics assessed by exacting methods is clumsy science. It is also a form of overt positioning for strategic, financial or political gain.

Building on the multiple arguments in Section 3 of this paper, classical irrigation efficiency is a term and measure with merit in the management of irrigation systems, and as such, should not be removed from the science and vocabulary of irrigation professionals. Alongside a basin allocation efficiency model, I contend that a bifurcating irrigation model offers an explanatory logic for boosting the performance of irrigation and river basin systems starting with farmers and their inter-farmer competitive concerns. Water demand and supply within and between different levels of a system are in a constant state of flux. It is this that makes matching demand and supply in one unit, in the face of competition from a neighbouring unit, and moreover of the opinions of their users regarding this balance, complicated and prone to mismatch. Mismatches leads to 'losses' that, although recaptured by the basin, are part of the physical and social equations of locally matching supply and demand. As such, irrigation would benefit from pluralistic and interdisciplinary approaches to irrigation efficiency. While there is great risk that efficiency will remain prone to public misunderstanding, political capture and imprecise scientific thinking, I believe the greater risk from eliminating CIE lies in what we are already witnessing–a retreat from a rigorous, multi-scalar and long-term engagement with irrigation performance, productivity and efficiency.

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