Towards an integrated theory of irrigation efficiency

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Abstract

In understanding and characterising irrigation efficiency, the conventional (or classical) approach and the IWMI 'effective efficiency' (neoclassical) approach hold true in various situations as long as the terms, circumstances and purposes of those situations are carefully defined. However, given the need to bridge these two views and engage with the specifics affecting efficiency, a theoretical framework of 'integrated irrigation efficiency' is proposed. The paper explores 12 issues that affect efficiency and that inform the new framework. Some of these issues are; the relevancy of scale in water management; the separation of design, management and monitoring activities; the relationship between efficiency and timing; and the coupling of net requirements and recovered and unrecovered losses. The discussion introduces the term 'attainable efficiency' and discusses the persistence of classical irrigation efficiency, hypothesising that it persists because it reflects observations made by irrigation professionals and farmers that local efficiencies and recovered losses critically affect water management and productivity in a river basin system.

***Key words:** efficiency, productivity, water management, design, assessment, and performance.*

Introduction

The subject of irrigation efficiency and productivity sits at the heart of one of the most topical water debates today – how to share water for human and environmental purposes. Water saving in agriculture has been suggested to be the solution to meet other sectors' needs particularly in developing countries (IWMI, 2002). Potential water savings are said to exist in surface irrigation systems, accounting for about 90% of total irrigation worldwide (Kay, 1986) where wastage is often quoted to be excessive (Jones, 1999; World Bank, 1993)). In addition, irrigation has been promoted as a key mechanism that can meet the future global food demands (FAO, 2002). Thus to meet both intersectoral allocation and produce more food and fibre, irrigation efficiency and productivity must increase. In this regard, the International Water Management Institute (IWMI, 2002) has initiated a Challenge Program on Water and Food arguing that; "In order to achieve secure water future and food we must improve the efficiency of water use by getting more crop per drop."

Mechanisms to increase efficiency are underpinned by a theory of efficiency – how to understand, describe, model, measure and interpret it. The debate, that has interesting parallels with other crisis narratives, is not just one of details over field methodologies but goes to the very heart of the significance of efficiency, encapsulated by the question 'does efficiency matter?' (Cai et al., 2001; Kay, 1999; Perry, 1999). Although considerable energies have been spent on constructing different models and viewpoints, as yet, knowledge about irrigation efficiency and productivity suffers from two critical gaps; a) an agreed theoretical exposition of the topic that cuts across different scales of water use and purposes to which efficiency is put to use; and b) a lack of an operable methodology that connects theory, field measurement, interpretation, design, management and assessment of irrigation systems. An agreed theory of irrigation efficiency is important because while many commentators are happy to believe in the widespread inefficiency of surface irrigation and hint at the progress waiting to be made, this position is unfounded and ill-informed. Also of concern is that an apposing viewpoint (that local inefficiencies are unimportant and that the need to improve local irrigation efficiency is unnecessary) becomes entrenched in mainstream thinking[1] as a generalisation. This is worrying because efficiency at the local level is bound up with equity, timing and scheduling, affecting the performance of irrigation, and with perceptions over water misuse, affecting the incidence of conflicts. Two positions have arisen on local efficiency, both potentially leading to misunderstandings and incorrect interventions to raise efficiency and productivity.

The dual-sided nature of the debate on the theory of irrigation efficiency is summed up as: if water reuse (recapture) is not included then lower measures of efficiency are obtained. If, on the other hand, these losses are accounted for in recapture then higher measurements of efficiency are found. The first position is described by classical measures of efficiency, while the second position is described by the neoclassical model (Seckler et al, 2003) of 'effective irrigation efficiency' promulgated by various authors from the International Water Management Institute (Keller et al., 1996; Molden et al., 2003; Perry, 1999; Seckler et al., 2003). Conventional irrigation efficiency (CIE) is defined by ICID (1978) as a ratio of average depth of water beneficially used to average depth of water applied, while Bhuiyan (1982) defined irrigation efficiency as a ratio of net irrigation requirement to the supply. Using these and other similar computations, efficiency of surface irrigation is held to be around 40%[2] (Gowing, 2002; Postel, 1992; World Bank, 1993).

The International Water Management Institute shows that such definitions do not include assessment of water that might be potentially available for reuse downstream, arguing that in river basins where drainage waters are reused downstream or from underlying aquifers, a water multiplier effect results in high irrigation efficiency when assessed at basin level. IWMI's key insight was to distinguish between diverted water and depleted water, the latter being truly lost from further re-use in the basin. Thus classical irrigation efficiency considers diverted water at the field scale to be "losses", but if the boundaries are redrawn to include a larger area, some of the drainage water is recovered for reuse (Gowing, 2002). Accounting for only depleted water means assuming re-use. In such situations, the 'effective irrigation efficiency' (EIE) may increase to more than double. IWMI termed savings that attempted to minimise losses that were anyway recaptured as being 'paper savings'.

Both positions appear to be theoretically sound within certain situations, but of importance to the debate on water savings and intersectoral allocation, are issues to do with how the 'situation' changes giving rise to different types of losses, whether they are easily recoverable and how such losses affect the timing of water movement through the landscape. This site relevancy aspect of efficiency is discussed by Wichlens (1999; 245). In effect, substantive questions remain: do local efficiencies matter, how do we interpret efficiency figures and if efficiencies are already high at basin scale what potential exists for savings?

These substantive questions, which reflect concerns of and observations made by engineers might explain why classical efficiency persists within the methodological toolbox of irrigation professionals. Seckler et al (2003) ponders on the "remarkable fact" (page 47) that neoclassical concepts have not been accepted, conjecturing that this is explained by on-going training in old ideas, a sense of professionalism constructed around classical ideas, by funding and financial incentives and by other political intentions. Yet, it is worth asking

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[1] *" ..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" The Independent (UK), "The Great Water Myth" By Fred Pearce. 28 Jan 2004.*

[2] *Literature on irrigation in Tanzania exhibits a 'received wisdom' that irrigation efficiency is less than 30%, sometimes as low as 15%.*

whether the paradigm has not shifted because the case is not closed; that classical methods are valid. Following a discussion in the next section to explore these questions, the paper proposes a theoretical framework around an integrating analysis of the subject.

Faultlines in irrigation efficiency

The next 12 subsections explore some major issues related to irrigation efficiency, in particular discussing questions posed by IWMI's effective irrigation efficiency.

Assumption errors

Arguments on both sides of the debate are built on frequently imprecise assumptions made about surface irrigation because of insufficient accurate quantitative data. Measuring irrigation efficiency is difficult and time consuming, covering the amount of net or gross inflows into the system, seepage, mean intake flows and a representative rainfall figure; losses in the distribution system and at the field level; the amount of water consumed by the crop (crop evapotranspiration); and the amount of water returned to its source river. These measurements need to capture different scenarios such as wet and dry seasons and wet and dry years, during which the crop water requirement, irrigation need, command area and efficiency all change. The parameters used for determining efficiency are rarely measured, obliging engineers to make assumptions often using generalised figures from the literature.

Much of the earlier work on classical efficiency by Bos (1990) and Wolters (1992) relied on a questionnaire approach. They found efficiencies existed between 15 to 42%, yet no assurance is given regarding the nature of fieldwork used to arrive at these figures either by the researchers or by their respondents. Of the 159 questionnaires many could not be used for accurate calculations (rates of incomplete data for conveyance, distribution and application efficiencies were in the order of 70%, 75% and 55% respectively).

In critiquing irrigation efficiency, the authors believe a 'debate problematic' exists from the use of circular logic; assumptions were made regarding low efficiency during design giving figures then were used to report efficiency as being low. Thus when protagonists of the IWMI paradigm critique interventions to 'save losses by lining canals' (e.g. Perry 1999, p 48) as examples of paper savings rather than real savings, it is critical to know whether such savings (even if 'paper') existed in the first place, or whether it was the assumptions about losses that were incorrect. In other words, the efficiency of irrigation might have been already very high, or savings need to be made by reducing non-beneficial evaporation; types of losses that irrigation professionals tend to ignore alongside the more well-known canal losses. Here, both CIE and EIE parties are incorrectly assuming the nature of the losses to be saved both in reality and on paper. It is often very difficult to correctly identify where losses are occurring, particularly those arising from system operation, but on the other hand commonplace to assume they stem from seepage from canal linings because of prevailing beliefs, design and lack of maintenance. The lack of such specifics feeds through to beliefs that 'most water is not lost' (Seckler et al 2003, p38) again without being backed by hard data.

The key insight from this discussion is that conventional irrigation efficiency needs to be critiqued and strengthened from within before moving to another model that incorporates some of the same theoretical problems and data quality weaknesses. The alternative to conventional efficiency is not necessarily effective efficiency, but an improved model of CIE.

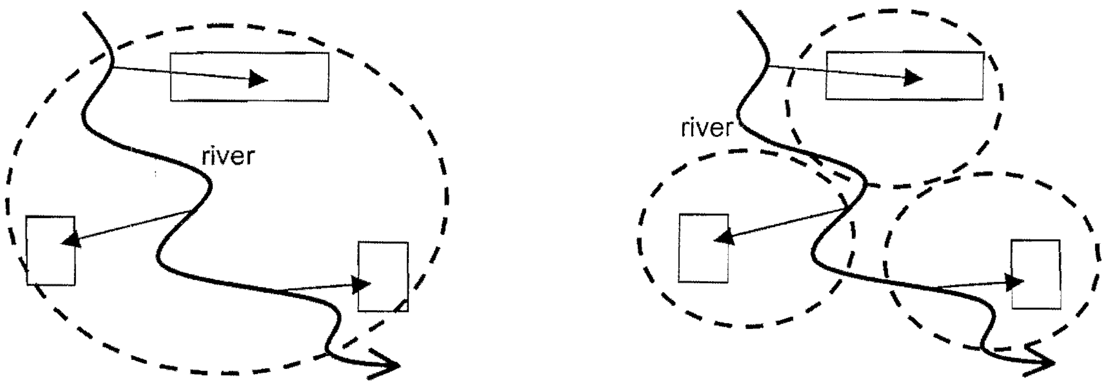
River basin perspectives: re-use or prior apportionment?

In arguing that local efficiencies do not matter, IWMI implicitly support the notion that it is acceptable for water to first pass through an irrigation system before an 'inefficient' fraction then becomes available for re-use. This is acceptable provided systems and losses are aggregated at the river basin with no loss in productivity, of useful information and scope for improvement of water management. IWMI's aggregation is depicted on the left hand side of Figure 1. A disaggregated view might be that if water management were sufficiently 'tight' then fewer recovered losses would arise – leading to a lower gross demand of the irrigation system. If this lower water demand was cascaded *up* the irrigation system so that less water was diverted, then the same water would remain in the river (or aquifer) for downstream uses. This disaggregated view could be seen as an *apportionment* model, where each irrigation system receives its own fraction or packet of water (see right hand side of Figure 1)

A disaggregated view reflects how irrigation systems make up a river basin and it is argued, is more quantitatively accurate and productive than the aggregated model because of various reasons argued in this paper. Namely; apportioned water moves more quickly to the lower system in the river rather than passing via an irrigation system; unrecovered losses are higher in the aggregated, reuse model because of unmanageable or difficult to manage coupling of unrecovered to recovered losses; the apportionment model allows a much more transparent identification of where losses occur and who is responsible for those (assisting in conflict resolution); the apportionment model suggests lower design costs if canals and turnouts are sized according to water efficient assumptions.

The pattern of water division and re-use in a river basin can be thought of as a scaled up version of an irrigation system. In the latter, the management of a limited supply of water aims to allocate the right amount of water to each part of the irrigation system, without relying on re-use to generate that supply. This depends on greater control of both quantity and timing in the conveyance and distribution systems. Similarly in a basin where limited water needs to be allocated in a timely manner, managers need to make a judgement on whether that best happens via the primary supply of rivers, canals and pipes, or whether some users best source their water from zones of recapture, whilst accounting for costs, water availability and associated social issues.

Figure 1. Aggregated (unitary) and dissagregated perspectives of irrigation river basins



The purpose of efficiency; design, management, assessment

To debate the theory of irrigation efficiency requires a clarification of the purpose of efficiency. The IWMI model of efficiency has focussed on the assessing efficiency of water management of river basins. Yet other scales and purposes are relevant. As well as river basins, another important scale is the irrigation system (see previous section). Furthermore, efficiency is used for three purposes; designing, managing and assessing (or modelling) the performance of systems. Perry (1999) reminds us that classical efficiency "is correct and appropriate for planning, designing and operating irrigation projects but is often dangerously misleading for understanding water resource systems' (p 46).

Regarding design, irrigation infrastructure has to be sized correctly with efficiency correction factors or the water requirement for the command area would not be met. In addition, engineers minimise structure dimensions to reduce costs. Design employs the conventional irrigation efficiency method, but often low figures of efficiency are chosen. This happens because either engineers build in safety margins or because they assume low efficiencies exist in reality. A 'low efficiency' can lead large intakes being deployed, which because of *actual efficiency* can lead to re-use of drain water (a point made above). Alternatively, if this water is not re-used, it can be drained back to the water source – and this case the lower design efficiency figure meant the canals, intakes (and possibly pumps) were oversized.

Returning to the question – which method should therefore be used for design – conventional or reuse? The answer, as the following examples show, is mainly the conventional method.

- Imagine a borehole supplying 10 hectares of land – for the purposes of designing the pump (say of 20 l/sec), the recapture of seepage water to the aquifer is of no interest in the design of the borehole capacity. The fact that there is seepage means that the conventional efficiency is lower, and this means the borehole capacity rightly needs to compensate; thus here the borehole will be bigger to supply its command area.
- Take a 'hill irrigation system' where a suitable plot of land has been found, but is two kilometres from a river, and there is no other land that can be irrigated using drain water from this system once supplied. Here, to size the intake, conventional irrigation efficiency is used because the conveyance and field application losses need to be accounted for.
- Imagine large surface irrigation system where each field is supplied by a tertiary canal. Again, here conventional irrigation methods would be used in order to size intakes and an array of canals and drains. The fact that the 'inefficiency' of the system generates excess drain water is of no consequence to the designer.
- With a drip or micro-sprinkler system, where losses are not recaptured (because net irrigation doses and losses are small) the classical efficiency model applies.
- Imagine, a re-use system as found in smallholder rice systems. Here field-to-field irrigation means that water draining from one field cascades to the next one. Classical irrigation efficiency does not explain this process, and the designer would probably be advised to use a method based on the re-use paradigm of IWMI, expressed as 'effective irrigation'. However, it is important to note here that re-use is an intrinsic part of field-to-field irrigation rather than arising from systemic inefficiencies. Yet, the classical method tends to fail because it sees an individual field plot as the final target for water supply rather than a collection of plots. If the latter were perceived as the final zone of depletion, then the classical model would work here.

In the last example, it was suggested that the re-use paradigm of IWMI might be useful in certain cases. However, a closer inspection of this method shows that while it might be good at explaining how efficiency increases with re-use, it does not currently lend itself to design planning. This is because the designer is unable to know (but might assume) the partition of losses into true sinks (such as evaporation and unrecovered seepage) and losses that are recaptured and re-used. As with conventional methods, these partitions need to be assumed – and yet, unlike the conventional method, guidelines or axioms when designing using the 'effective efficiency' method have not yet been established.

The next purpose requiring the utilisation of efficiency is the management of water. Management aims to operate infrastructure to schedule the right amount of water to the correct location at the right time. Performance increases as a result of meeting livelihood and crop water requirements in a timely fashion. Here we argue that raising conventional irrigation efficiency improves water control and irrigation scheduling. Here we are in agreement with Perry's statement given at the beginning of this sub-section.

Thirdly, efficiency plays a part in assessment and modelling. Assessment is the monitoring of the accuracy and efficacy of design and management of chosen outcomes (e.g area irrigated, days in deficit, volume applied). Modelling is grouped with assessment because of the manner in which performance can be estimated from other proxy indicators in a model. At the irrigation system level, CIE is one criteria of evaluating the performance because CIE is relevant to the operation of that system, though EIE may also be determined as a step in assessing the ratio of recovered and unrecovered losses should that information be useful. At the basin level, effective efficiency is relevant but only if the basin is aggregated as a unitary basin. However, it would also prove possible to determine a picture of the basin from a cumulative picture of the individual dissagregated systems, in which case CIE also is relevant.

Regarding Perry's comment '[CIE] is often dangerously misleading for understanding water resource systems', the authors argue that on the contrary our understanding of water resource systems is built up from an appreciation of factors other than water assessment at an aggregated basin level. CIE is part of the understanding of water resources because it applies to the design, operation and assessment of irrigation systems and to a disaggregated picture of irrigated basin performance. These are substantive parts of the water management picture.

The conflation of efficiency and productivity

The productivity model of IWMI draws our attention to multi-use/user benefits from water re-use as well as consumption providing conjunctive benefits. For example, fishermen that use canals and tanks for fisheries clearly utilise irrigation water in ways that contribute to their livelihoods and to the regional economy. In this respect, the productivity emphasis is useful.

However, IWMI appear to argue that irrigation productivity is a replacement of efficiency. As one senior IWMI manager said, "IWMI as a matter of principle does not like the term efficiency because of its many conceptual problems; we prefer thinking about productivity of water". This convenience comes from two ideas. Firstly, there is the argument that it is important to focus on the *benefits* of water (income, jobs, crop production) as a ratio of water used. Secondly, was the recognition that since water is reused sequentially in a river basin, these benefits should be expressed against a volume of water that moved from user to user. Therefore, it was less necessary to express benefits as a ratio of net water used in any one particular area of the basin (e.g. a field or irrigation system) but instead to express this as a proportion of the total water depleted from the whole basin.

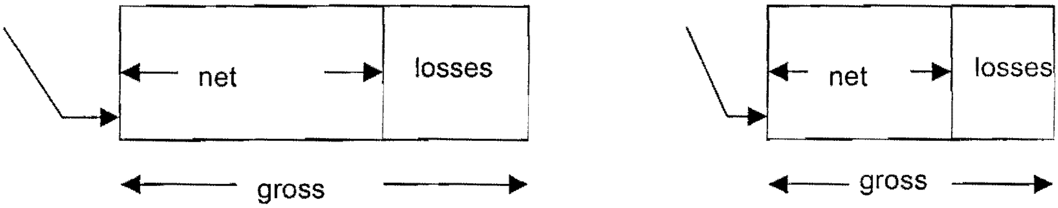
However, this paradigm-shift should not obscure an important question; is efficiency a sufficiently different issue than irrigation productivity to be of importance in water management? Here, it is argued, the debate has to recognise differences between efficiency and productivity, and the significance of that difference for water management. Productivity is an expression of the bio-economic output from the gross amount of water depleted. While this is an important indicator, it underplays the role of the denominator in establishing the productivity and fails to recognise the details and management of, and policy-work related to, the efficiency of water. Efficiency contains a ratio of net to gross depletion of water – both of which can be altered as a way of increasing efficiency and productivity returns to water. The key point is that efficiency rather than productivity that links more directly to the complications that make up the management of irrigation water.

Each term, productivity or efficiency, relates best to prevailing interests. Productivity is of importance for decision-makers at the basin scale, when comparing between sectors or major water system types or basins. Yet, efficiency is more relevant for the managers of water at the irrigation system level. Another pertinent point here is that if a river basin is dominated by irrigation, then efficiency of water management becomes critical in ascribing the productivity of that particular system or basin or in defining how much water might be available to other users by making savings within irrigation. Thus, irrigation efficiency remains a meaningful part of the discussion on water productivity, allocation and distribution.

Coupling net irrigation demand and losses

The authors argue that for a given net irrigation dose at the field level, the losses, recovered and unrecovered, are closely linked or 'coupled'. This can be seen when better in-field control reduces the total dosage per irrigation event which not only reduces the net irrigation demand, but also minimises losses. By accumulation, the 'per irrigation' event coupling adds up to a seasonal and system coupling. This idea is expressed in Figure 2, where a larger net dose, on the left hand side, is associated with a larger proportion of losses.

Figure 2. Coupling of net demand and size of losses



The degree to which net irrigation and losses are coupled probably depends on the nature of the irrigation system, crop and soil type, hydrology, and topography. In turn the coupling might be disproportionate, proportionate or non-existent. Thus in drip irrigation, the coupling might be minimal but proportionate since a larger net dose gives rise to larger losses. In complex large irrigation systems with few canals, coupling might be stronger and more disproportionate with losses becoming much larger as the net dose gets bigger.

It is also important to note that the recovered and un-recovered types of losses (see below) are closely coupled in irrigation systems. This mirrors the coupling between the net dose and losses, except in this case higher recovered losses probably mean higher unrecovered losses. An example from Usangu is associated with the head difference required to drive water from plot to plot (with high friction losses) on a system with very few canals (Figure 5 might help visualise this discussion). Contrast this with an irrigation system with canals where water can be driven to tailend areas with a lower head difference. The coupling exists because part of the head difference 'wedge of water' later passes to tail end plots (i.e. recovered losses) while part evaporates (unrecovered losses). A canal network would store less water and give rise to less water lost via coupling of the recovered and unrecovered losses.

The key insight here is that because the two types of losses are coupled, it becomes very important to minimise the recovered losses so that the unrecovered losses are minimised. From this, we argue that CIE which accommodates both types of losses is relevant.

The presence and expression of recovered and un-recovered losses

The explanatory power of the IWMI paradigm is partly related to how it arose. It is the belief of the authors of this paper that the IWMI paradigm principally applies to river basins where a specific set of circumstances occurs. Interestingly, these circumstances reflect the original geographical emphasis of IWMI work on Asian and South East Asian irrigation, dominated by continuously cropped and irrigated rice. (In addition, observations from irrigation systems in the USA explain the trade-offs between upstream efficiency savings and reduced water sent downstream (Seckler et al, 1996).

The IWMI paradigm works well where near-surface aquifer and flood-plain agriculture is found to constitute a significant proportion of the river basin irrigated system or where the hydrological endowment helps to drive recoverable losses. It is in circumstances such as this that water re-capture is more a part of the hydrological system and where large and continuous amounts of water are being used in irrigation and are finding their way back to being a source for other irrigators. In other words, the proportion of water that constitutes local unrecovered inefficiencies is sufficiently small for it not to be of concern.

Thus the re-use scenario of IWMI holds true for situations where 'easy' recovery exists; i.e. field to field irrigation where excess use in one field drains through and helps supply another field. Scaling up slightly, the re-use model works well where excess use of water in one irrigation system feeds drainage systems that re-supply the water needs of a peripheral irrigation system that is dependent on that water. The total production of both systems needs to be accounted for in a water productivity analysis. A third clear example exists when aquifer water is tapped for irrigation which then via local 'inefficiencies' drains back into the ground, re-supplying the aquifer to be re-used.

In other cases, the IWMI model, or rather the generalisations drawn from it, may not apply so accurately. Irrigation in Usangu, Tanzania for example, is an example of dynamic irrigation found on relatively impermeable soils of a savannah plain. Here the major part of losses occurs via sinks and non-beneficial evaporation (Machibya 2003) – in this case the generalisation that local losses do not matter and that most losses are recaptured does not hold true. In such cases, improving the classical efficiency of water management results in real water savings.

Key to the debate on the relevancy of the IWMI model is an understanding of recovered and unrecovered losses (where the latter are losses to sinks or non-beneficial evaporation in the IWMI model). Table 1 contains a simple framework of recovered and non-recovered losses, each with three types of losses; seepage, runoff and evaporation. Table 1 shows that non-recovered losses, particularly under the non-beneficial evaporation, are very real possibilities in irrigation.

Table 1. Irrigation loss partitions

Loss partition	Class of loss	Examples
Loss recovered (recaptured)	Evaporation	Note: Unless greenhouses are utilised, evaporation cannot be recovered in field situations
	Seepage	- Lateral seepage from a field, possibly accentuated by poor maintenance and compaction of bunds - Below root-zone seepage that feeds a water table that is reused or that then supplies surface water downstream that is then tapped
	Runoff	- Excessive drain water from fields reused downstream - Drain water that come from meeting the depth of application required at tail-end of fields

Loss not recovered	Evaporation	- Evaporation from canal and field conveyance of water to meet net demands arising during growth period - Excessive wetting up during field preparation delays, resulting in unrecoverable ET_o - Evaporative losses of water from poor field definition and irregular boundaries - Excessive period of field watering at the beginning and end of net crop season - Excessive depth of water, evaporated at the end of season in paddy basins, also related to poor uniformity of field water depth, - Depth of water related to 'wedge' of water to create head-difference to 'drive' for field-to-field conveyance.
	Seepage	Field seepage to deep percolation which is unrecoverable within defined system boundary (e.g. enters geological aquifers for weathering of parent material or re-emergence beyond zone of interest)
	Runoff	Drain water that exits re-use system zone (either as surface flow or ponding followed by evaporation) without being captured. For example, the drain might be too deep to allow for abstraction.

Attainable efficiency: avoidable and unavoidable losses

Managing efficiency requires us to judge whether losses are manageable (avoidable) and unmanageable (unavoidable). One facet of both conventional and effective efficiency figures is that the numerator of the equation is often the net crop water requirement. Achieving 100% efficiency becomes an impossibility. The denominator includes all losses, whether or not they are manageable. This arrangement begs the question of whether we need to set numerators and denominators that makes interpretation of results realistic and useful.

Although this goes to the heart of defining what is beneficial and non-beneficial process and non-process depletion (developed by IWMI) we leave aside this discussion to focus on 'attainable irrigation efficiency' (AIE). Attainable efficiency is based on the concept that some losses (which may be recovered or non-recovered) can easily be reduced, while others not unless considerable effort and cost is expended. Thus, evaporation from canals during conveyance is unavoidable but evaporation occurring from a long period of presaturation wetting of a rice field is avoidable and manageable.

Attainable efficiency is based on two cases of water management; target and found. 'Target' is the attainable amount of water depleted (or diverted) in growing a crop, and includes water at the system, field and crop level. Target is normally taken from observations of practices where water is short and care is being taken to minimise losses, perhaps at the tail ends of systems. 'Found' water is the existing case of water depleted or diverted based on observations of more profligate water use, seen more commonly at the top end of irrigation systems. Attainable efficiency is therefore:

AIE % = [target irrigation depletion] / [found irrigation depletion]

Some form of judgement is required in determining what is an achievable target. Thus in rice, the unavoidable seepage below the root zone (say 2 mm/day) is often included in the net field level demand calculation and therefore would go into the 'target' numerator and 'found' denominator. In other cases, differences in practices might inform the process. For example in tail-end areas in Usangu, farmers will transplant only 3 days after first receiving water, while top end farmers will do this in 7 days, and the formal state farms will wait for nearly 30 days. In each case the non-beneficial evaporation increases from 3 to 7 to 30 days worth, becoming an increasingly higher proportion of the total depletion.

While each situation will provide cases that allow such judgements on the manageability of losses to be drawn up – the key point here is that such judgements on the local nature of efficiency should be made, leading to the specification of the local or regional 'attainable efficiency'. In this respect the argument that local inefficiencies do not matter should be treated with some caution.

Farmer responses to efficiency

Farmers behave in ways that demonstrate local efficiency matters. In water scarce situations, farmers will organise themselves and adopt technological options that improve water distribution or express views that reveal their impressions on water wastage and control. Examples from Tanzania include tail-enders on the Kimani irrigation system that feel their top-end neighbours are wasteful because water "should be ankle depth, whereas they take more". In systems in the Mkoji-Subcatchment in Usangu, dry season irrigation is concentrated in upstream areas around the intake because seepage in canals means that after about a kilometre or two, the water supply dwindles (and there is no shallow aquifer from which to abstract this water except for domestic purposes). Following a drought on the Kapunga Smallholder Scheme, farmers drew up new stronger guidelines to minimise absentee growers that caused empty plots to be wetted up without being planted to rice. Some of these farmer's concerns reflect the time dimension of water management, discussed in a sub-section below. Thus, similar to the point made in the previous section, evidence and observations can point to the fact that local efficiencies play an important part in water management practices and in determining the productivity of water at all scales.

Relationships between efficiency, productivity, time and timing

The substantive critique of the IWMI perspective that local efficiencies do not count is that the time aspect of efficiency is largely omitted. Since water-related benefits accrue to *living* things (humans, crops, plants, animals) timeliness of water arrival is of paramount importance. Put crudely, if water arrives a week after a crop has permanently wilted, then no amount of that water will resuscitate that crop. Three scales; field; irrigation system; and river basin show the relevance of the timeliness of water to the discussion on efficiency and productivity, as discussed below. Two processes, related to the route taken, affect timeliness; the velocity and the route length of water movement.

Field scale timeliness
Here the argument is to keep as much of the available supply as possible for effective, timely watering work. In rotational irrigation systems, control of water affects the ability to schedule irrigation on time, and in continuously supplied systems, it affects the ability to achieve wetting up within narrower rather than longer time frames. The relationship between water losses on timing of water delivery is complex but essentially arises from the rearrangement of the following continuity equation (Lankford, 1998):

Hectares irrigated = [l/sec x hours x 0.36 x efficiency]/mm applied

Hours = [ha x l/sec x 0.36 x efficiency]/mm applied

This means that the time is related to the dose, area, efficiency and flow rate of the rotational leadstream (main d'eau). If the soil holding capacity of 65 mm is to be refilled over a rotational block area of 90 ha, using a flow of 70 l/sec then with an efficiency of 100%, a cycle time of 9.7 days or 232 hours on a 24 hour cycle is required. From now on most key variables are fixed; the evaporative rate, the soil moisture replacement target, the flow rate, and therefore the hours required to complete the cycle. If the efficiency drops to 80%, the time to complete increases to 290 hours, and evaporative rate implied by this is now 5.4 mm/day. Hence, a lower efficiency, which can arise either across the whole rotational unit, or from one or two fields within it, can impair the ability to schedule water on time, and the delays in rate of progress of irrigation can be converted to millimetres of stress below the management allowed deficit.

In the example of the continuously supplied rice irrigation system, a deeper standing water layer in a proportion of the irrigation are can hold back water from arriving and supplying a tail-end area. For example an area of 900 ha utilising 22 cm of water when only 12 cm of water is required is storing an excess volume of 900 000 m^3. (These differences in depth are not unusual in top-end fields found in Tanzania.) Assuming that in wetting up new lands, 250 mm is required in presaturation of soil and an additional 120 mm is required in the standing water layer, this 900 000 m^3 could supply an extra area of 243 ha, a gain of 27% in area. However, the argument here is not that an extra area is supplied (in itself a bonus), but that this 243 hectares begins to receive its water earlier than it would if it were to wait until farmers began to release water over and above 22 cm. Thus the rate of transplanting is partly controlled by efficiency.

At the irrigation system level of the hydrological system, we see that delays arising from excessive water usage in one upstream irrigation system may result in impaired productivity in a downstream system. Here, water that moves through an inefficient upper system takes more time to arrive at the lower system – although once it has arrived, the flow is then steady. A case study from southern Tanzania explains (Machibya 1993). A large-scale state farm of 3000 ha is surrounded by a peripheral ring of smallholder farmers occupying some additional 640 ha. The drainage water from the state farm supports the tail-end farmers. There are still timeliness issues associated with the fact that water has spend time on the state farm before routing via the drains to the peripheral farmers. In this case the productivity is lowered because the lower system is planted nearly 30-60 days later, resulting in lower yields due to photosensitivity and seasonality, and due to 25% lower market prices. What this also highlights are the interactions between local efficiency, land area, transplanting timing, labour and inputs. Farmers, given the choice, would wish to plant earlier to catch better prices.

At the basin scale, the presence of irrigation and irrigation losses affects timeliness and the shape of downstream hydrographs. Thus, water that routes via irrigation schemes back into the source river rather than remaining in the source river is subject to delays. These delays occur via two routes; water moving in surface channels and water moving to groundwater. First, in Usangu, water moving in canals and drains that are choked with weeds and blocked for fishing, and via fields to drains, can take between 6 to 10 days to reach tailend farmers. A simple calculation based on actual measurements demonstrates this. A range of river flow measurements gives an average velocity of 0.8 m/sec in Usangu - thus water takes about 8 hours to travel a 25 km stretch. Routing via canals and fields this water is estimated to move at speeds of about 0.2-0.05 m/sec, which on average (0.125 m/sec) would mean that water this water would take about 55 hours.

Secondly, water moving via groundwater seepage and recharge of rivers can take weeks and months. Focussing on the IWMI argument that groundwater losses are recaptured, it is not clear that the groundwater flow in Usangu is to places where it brings 'desirable' outcomes. Prior to 1990's the Great Ruaha River was perennial, and now it is seasonal, dry for between 2 to 6 weeks per year. If water is being returned via a groundwater movement, it is not evident in that particular stretch of the river. Instead the Usangu recharge may be supplying a number of smaller springs along the East African Escarpment that provide local benefits but not the large-animal and aquatic ecology previously found in the Ruaha.

This result of these changes in routing are evident in Usangu where although the total volume passing through the Ruaha National Park may be important, the time distribution of the volume is very significant, whereby low and zero flows occur near the end of the dry season.

The IWMI model depicts water movement as continuous or instantaneous. The IWMI viewpoint applies well to agro-ecological zones where stability in water supply and demand tends to hold and where water is always flowing in similar ways throughout the annual cycle. This means either the climate is tropical and allows year-round cropping, for example in parts of South East Asia, or the water supply is sufficiently consistent to allow the same. Examples of this are found in the lower reaches of the Nile, and on some of the larger rivers of the Indo-Gangetic Plains. The effect of these climatic/water supply factors is to create a calendar where differences between seasons and months is relatively minor, or more accurately put, 'forgiving' of delays in water arrival. In such agro-ecological zones, rice can be continuously cropped, or start and finish dates of a rice/wheat cycle slide into each other.

However in areas with marked seasonal changes, or where groundwater is not rapidly returned to surface hydrology (or abstracted by pumping), then losses within irrigation, and their associated routing paths, can result in a shift in the a hydrograph that may be detrimental to downstream users. Classical efficiency plays an important role in ephemeral or seasonal rivers where water has to be used within a specific window of opportunity.

The affects of seasonality on efficiency

In most texts on water management, irrigation efficiency is held to be static, and an artefact of various design and management variables. However, research in Tanzania (Machibya, 2003) shows that the climate (wet and dry years) has a considerable effect on the amount of water being received by an irrigation system from both increased canal water and rainfall. This in turn affects the efficiency of the system because of the response to changing scarcity by farmers. The classical efficiency of Kapunga farm in the dry year (rainfall 300 mm) was measured at 48%, and in a wet year at 35% (rainfall 820 mm). Although seasonality affects both efficiency models similarly, we argue that efficiency is case specific, and should be calculated for two main types of climate scenarios – normal to wet years and dry years. This allows for the diverted and depleted water to be more accurately determined in each scenario.

Interactions with command area dynamics

The role of command area in irrigation efficiency is rarely explored, yet command area, efficiency and productivity are connected through three relationships:

1. The irrigation continuity equation
2. The configuration of irrigated and irrigable areas
3. Equitable distribution of water between areas or systems

Firstly, command areas are related to irrigation efficiency, through the equation:

$$\text{Hectares irrigated} = [\text{l/sec} \times \text{hours} \times 0.36 \times \text{efficiency}] / \text{mm applied}$$

The equation says that if all else is fixed, as efficiency increases, the area irrigated goes up. Thus, in Keller et al (1996), the improvement in efficiency results in expansion of farms where efficiency savings have been made, resulting in less water moving downstream (p 11).

However, secondly, the area response to efficiency is dependent on the configuration of irrigated area and irrigable (or expandable) area because this determines where expansion occurs. The local expansion observed by Keller et al (ibid) is because local irrigable area existed (Figure 3). Yet this configuration need not always apply; instead the irrigable area could lie downstream, which could then become irrigated with the saved water delivered from upstream areas (see Figures 4 and 5). Thus depending on the configuration of irrigated and irrigable area, paper savings can result in areal growth of irrigation in downstream areas.

Figure 3. Configuration 1. Savings in irrigation efficiency occur upstream since spare land exists on farms where savings are made

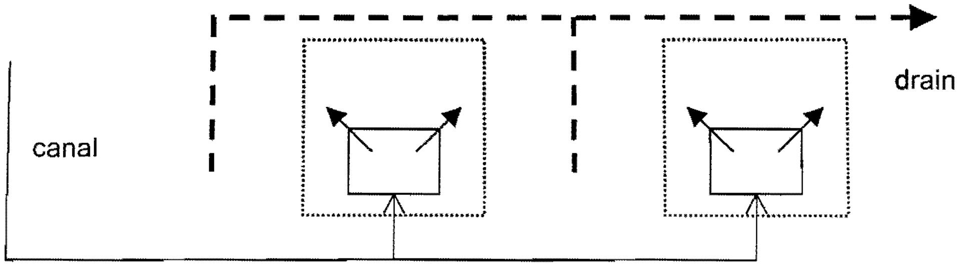
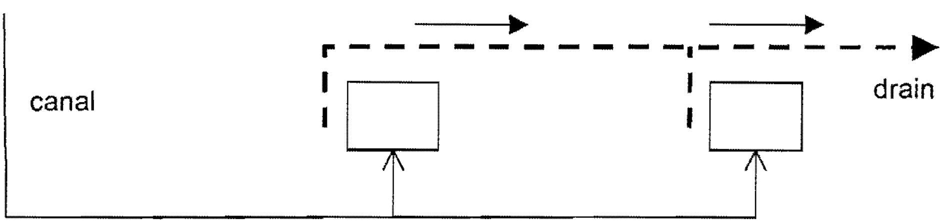
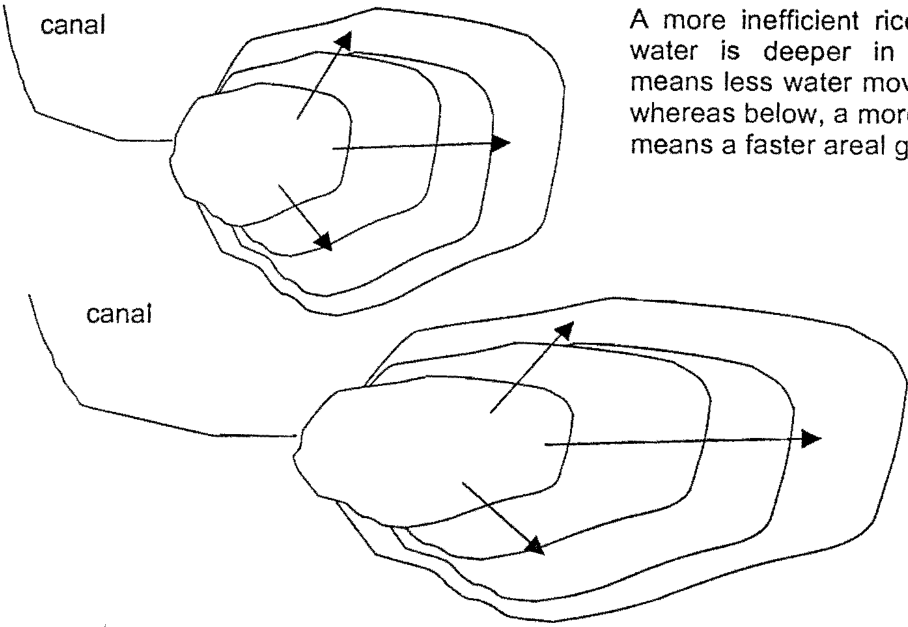


Figure 4. Configuration 2. Savings in irrigation efficiency occur upstream, but without any area to expand into these savings are sent downstream.



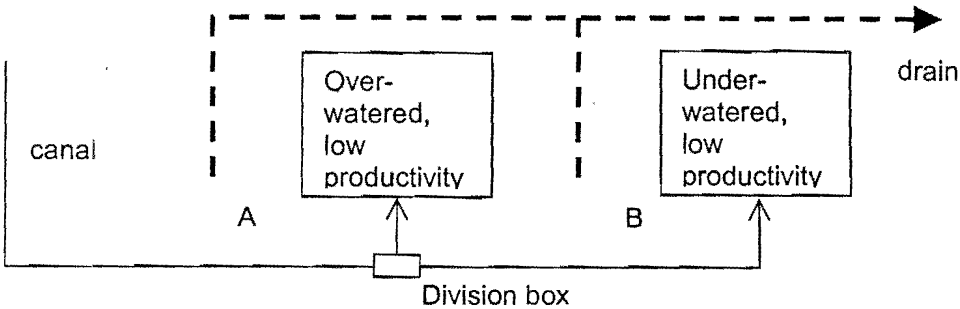
Thirdly, equitable allocation *between* command areas on the basis of efficiency improvements is necessary because of the 'productivity curve of water'. This term expresses the crop response to increasing amounts of water and the diminishing returns to greater applications of water. In other words not all water is equally productive. An under-irrigated field results in poor yields, but excessive water to another field does not give excessive yields that compensate for the under-irrigated field (see Figure 6). It makes sense to even up the productivity of water so that for water used in a command area, maximum yield is obtained. The reason that efficiency is involved here is that by design or by management a flow-to-area ratio that may be correct at the secondary level may be divided incorrectly at the tertiary level. More efficient management of water in Block A in Figure 6, would, if adjusted for at the division box would cascade water to Block B.

Figure 5. Configuration 3. Concentric expansion occurs faster downstream as savings are applied in areas that have already received their water



A more inefficient rice system, where water is deeper in top end fields, means less water moving downstream, whereas below, a more efficient system means a faster areal growth

Figure 6. Effect of inequitable ratio of flow to area on efficiency and productivity



Block A is less efficient, but is taking B's water, so total productivity is low

It is important to determine how savings in local efficiency affect productivity and might result in the expansion of areas *in situ*, or downstream or both. It is misleading to summarise that increasing efficiency in upstream areas does not release water to downstream areas because this cause and effect is dependent on the configuration of current and expandable irrigated areas. This has important implications for the choice of CIE and EIE in making decisions about whether local efficiency matters. The authors feel on the basis of this discussion that the default position should be that saving water is desirable to allow those savings to be purposefully used elsewhere (even if on the same farm). This is preferable to a situation where water 'finds' itself somewhere else by a random pathway of seepage, drainage, recapture and re-use.

The role and permeability of boundaries

Boundaries play a critical role in the theory of efficiency. In classical efficiency, boundaries are implicitly defined at the field level. In effective efficiency, boundaries are implicitly set at the basin level. Such boundaries are not set out of convention, but represent a degree of permeability for water accounting purposes. Water accounting is applied to a unit with a relatively impermeable boundary across which water tends not to flow (e.g. river basin interfluves or a field acting as a sink). We propose that five boundary types exist; geo-political, irrigation typology; sectoral, sub-surface and surface drainage. These depend on the situation being studied so that intermediate or pertinent conditions can be reflected.

The presence of international or other geo-political borders cutting drainage lines might define the limit of the extent of re-use of water in any given analysis. Thus irrigation efficiency is described as a national or geo-political phenomena. Such a situation can be found in the northern part of Swaziland, where drainage from sugarcane estates directly and immediately flows into South Africa. This water is re-used, but from the perspective of the sugar estates, it cannot be taken into account when exploring the latter's efficiency. This is because the water cannot be recaptured into Swaziland, and neither can the resulting produce be claimed as Swaziland's.

A shift in irrigation typology might also define boundaries of re-use. For example, interest in efficiency might be applied to an irrigation system with very specific product, technology and cost. In the Pangani Basin in Tanzania, flowers are trickle irrigated – although arguably there might be some downstream re-use, the analysis of efficiency of irrigation is strongly defined by the investments made in terms of farming systems, technology, water rights, labour etc.

Sectoral boundaries define limits of irrigation efficiency analysis. In Usangu, Tanzania, the presence of a wetland halts any downstream recapture of water for irrigation. Similarly, urban land, protected parks and other defined land uses demarcate the limits of water re-use.

Sub-surface drainage to aquifers define a potential re-use zone where boreholes tap into a common groundwater body. In reality, groundwater might be highly variable or be held within clay materials with a high matric potential, precluding sensible or cost-effective reuse. Alternatively, groundwater might be too deep or saline to be economically viable. We argue that it is not realistic to present a default position that seepage below the root zone is automatically available for re-use and therefore constitutes recoverable losses.

Drainage boundaries might also affect the selection of the re-use area. Often, canals take water by gravity down the contour line of one bank of a river, allowing water to flow across the interfluve and then drain into the basin of a neighbouring river. The re-use of this water need not be included in the calculation of productivity of water of the original basin.

Here the key insight, is that for each case being studied, the local boundary conditions need to be explored and defined. The nature of the boundaries defines whether water remains recoverable for re-use or not.

A framework for integrated irrigation efficiency

In the discussion above, we found that the classical method of defining irrigation efficiency has value for a number of purposes at different scales. Table 2 presents a framework for integrating the classical and neoclassical perspectives together, subject to the purpose and scale of the intervention. There are three main purposes; design, management and assessment (discussed above in more detail) and two main scales; system and basin.

Regarding scale, irrigation systems denote individual systems that receive their water from a pump or intake or parts of those systems (e.g. a secondary canal). 'Basin' denotes a boundary (e.g. catchments or sub-basins) in which two or more irrigation systems are connected either via mutually exclusive subtraction of river water or re-use of water drainage or a combination of both. This latter distinction is important because the integrated irrigation efficiency (IIE) framework recognises the *manner* in which irrigation systems are connected.

Whereas the IWMI model assumes that "most of the water remains in the hydrological system" (Seckler et al., 2003) and that losses are recaptured, this does not always hold true. Non-beneficial losses through evaporation or to seepage that cannot be recaptured means that individual systems are strongly connected to each other by their *inefficiency of water use*. This means that a basin perspective can be built in two ways (see Figure 1); by assessing water depletion only at an aggregate unitary perspective of the basin, or by summing the performances of disaggregated individual systems. The latter is useful when we seek to see to know where and how we can improve the performance of the whole basin by tackling the constituent parts. These perspectives set up different ways of making policy decisions.

Table 2. A framework for integrated irrigation efficiency (IIE)

Scale and purpose	Notes	CIE	EIE	AIE
System* design	Procedures to design infrastructure	Applicable	Not applicable	Can be applied
System management	Activities designed to improve timeliness, equity & reduce losses	Applicable	Not applicable	Applicable in 'diverted' form
System assessment or modelling	Performance monitoring to assist management	Applicable	If system is the sole perceptive, then not applied	Applicable in 'diverted' form
Basin management	Interventions to improve intra and inter-sector sharing of water	Applicable with segregated perspective	Applicable with an aggregated perspective	Applicable in 'diverted' form
Basin assessment or modelling: summation of individual systems	Modelling & performance monitoring of whole basin from disaggregated systems	Applicable	Not applicable	Applicable in 'diverted' form
Basin assessment or modelling: an integrated whole	Modelling & performance monitoring of whole basin from unitary perspective of individual systems merged	Not applicable	Applicable	Applicable in 'depleted' form

Notes: * system or part of system. CIE; classical irrigation efficiency, EIE = effective irrigation efficiency, AIE = attainable irrigation efficiency.

Figure 7 is a schematic model of integrated efficiency, which is only briefly introduced here. Several key features of the diagram define the IIE approach, which could be incorporated into a more complex quantitative model of efficiency:

Five types of losses are found, non-beneficial evaporation, unrecovered and recovered runoff, and recovered and unrecovered seepage.

Diversion flows, Q div, are constrained by an intake or pump capacity. This affects the amounts of water flowing to the primary use system as well as any re-use systems.

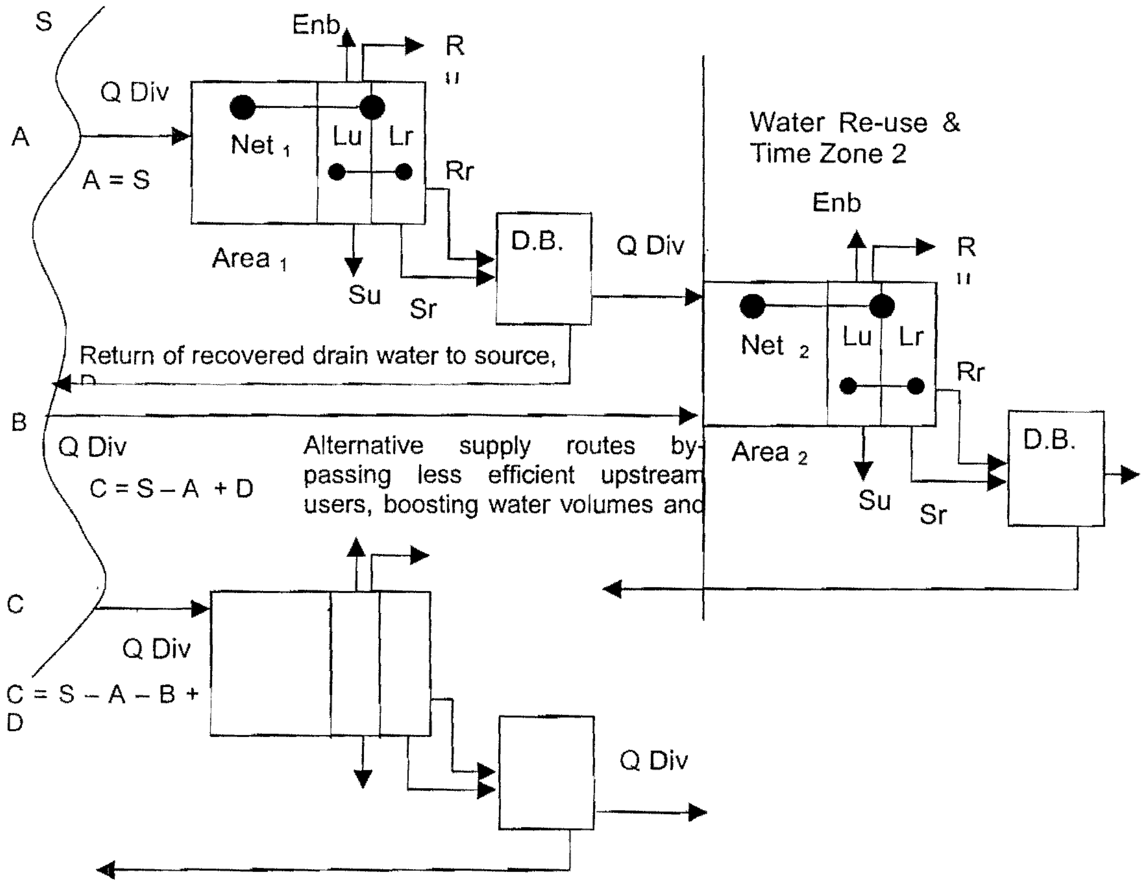
Reuse is found in another area and time zone. This reflects the delays that arise via re-use.

Downstream source flows are connected by subtraction from upstream diversions as well as by return flows from upstream systems.

Recovered and unrecovered losses are coupled, as are net water requirements and losses.

Before reuse can occur, water has to first enter a conceptual 'drainage box' so that water is either re-used or returned to the source.
Related to timing, flows to re-use systems could be supplied more directly which improves timing and reduces the delays that arise from reuse (see intake B).
The river basin consists of a number of intakes (A, B, C in the diagram), this reflects the need to first examine individual systems before aggregating at the basin level.

Figure 7. Integrated irrigation efficiency for reuse and apportionment



S = source, river or aquifer
A, B, C = three intakes for systems A, B, C
Area = area for cycles 1, 2, x
Net = net water demand for cycles 1, 2...x
Lu = Losses unrecovered (to sinks)
Lr = Losses recovered (to next cycle or to source)
Enb = Non-beneficial evaporative losses

Su = Seepage losses (unrecovered)
Ru = Runoff losses (unrecovered)
Rr = Runoff losses (recovered)
Sr = Seepage losses (recovered)
D.B = Drainage box
D = Recovered drain water to aquifer/river source
Q div = intake/pump capacity for diverting water

Conclusions

The debate on irrigation efficiency can come down to a summary position; "surface irrigation is very inefficient" or "local inefficiencies do not matter". The summary position of this paper it is that "efficiency is site, scale and purpose specific and that recovered losses matter locally". The site-specific nature of irrigation in a river basin and its 'fit' with the conditions within the basin should be examined carefully. A more complex, dynamic and seasonal picture of irrigation efficiency is required if we are to ask questions about how much, when and where spare water can be found from irrigation to supply other users. Judging efficiency indicators for systems should be seen as not straightforward. This site-specificity allows managers examine local attainable efficiencies and to tailor interventions accordingly (e.g. where water may be cost-effectively released downstream). Efficiency is also task or purpose specific, distinguishing between designing, managing and assessment. The cumulative effect of local efficiency on local productivity summarised at the basin level is different to a unitary basin perspective constructed from homogenising local systems and their many variations.

Related to the 'management' task, the authors believe that water should be managed optimally and efficiently where it is being used. This simple maxim addresses the inefficiencies that farmers at the local level observe and articulate, thereby improving returns to water by building on the benefits of local 'co-operative competition' between farmers. In addition, these improvements can be made year on year. Local care benefits interactions between timing, volume, labour, inputs and charges, land planting, prediction, reduces overall planting schedule and season length, and minimises proportion of water which goes to non-recoverable losses because net water and recovered and unrecovered losses are coupled. Lastly, it ensures that outside the irrigation system, improved timing of water is delivered by rivers rather than by drainage, reducing unavoidable losses due to this. We also argue that improving local efficiency is worthwhile because of the inherent problems associated with recapturing losses to source rivers via drains. Farmers go to great lengths to obtain water, but are woefully neglectful of water drainage distribution once it has passed beyond their boundaries. Local efficiency matters because this fits closely with making every drop count, which IWMI implies through the expression 'more crop per drop'. Yet strangely the IWMI paradigm also seems to equate with tropical water abundant river basins in which transference by alternative routes matters little in terms of losses or timing.

Finally, the paper argues that efficiency is a sufficiently rich topic for analysis and discussion without it being subsumed into productivity. By over-emphasising productivity and discounting efficiency (rather than allowing both), the neoclassical model allows for productive but inefficient use of water. Productivity now includes too many factors within it to isolate efficiency factors that need to be accountable and transparent. We believe an accommodation of these irrigation complexities is necessary by debating irrigation efficiency fully, giving classical efficiency greater credibility, therefore not only allowing it to persist, but placing it correctly within the science of water resources management.

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