Agricultural Water Management 108 (2012) 9–15

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Efficiency and productivity terms for water management: A matter of contextual relativism versus general absolutism

Gerardo E. van Halsema*, Linden Vincent

Irrigation and Water Engineering Group, Centre for Water and Climate, Wageningen University, Droevendaalsesteeg 3a, 6708 PB Wageningen, The Netherlands

ARTICLE INFO

Article history:
Received 17 December 2010
Accepted 30 May 2011
Available online 22 July 2011

Keywords:
Irrigation efficiency
Water use efficiency
Water productivity
Consumptive use
Economic water productivity
Water valuation

ABSTRACT

Growing water scarcity and increasing demands for agricultural products generate much debate about improving the agricultural sector's water use efficiency and productivity. Agricultural engineering traditions feed this debate with notions such as agricultural yield gaps and low water use efficiencies that draw attention to potential improvements. However, when perspectives are shifted from an irrigated field to a river basin, someone's (water) loss may be another's (water) gain. Such shifts in perspectives complicate the applications of our concepts of irrigation efficiency (IE), water use efficiency (WUE) and water productivity (WP). This paper studies the use and abuse of definitions and applications of concepts of IE, WUE and WP and examines their appropriate application for different scales and domains of water use. In this paper we argue that water management decisions are best informed by using IE and WP at the irrigation scheme and catchment level, respectively. This use can identify context specific opportunities and potentials for increased water use efficiency and productivity as well as the potential trade-offs in water re-allocations between diverse water users and uses.

1. Introduction

As competition for water increases and commitments to sustainable ecosystems grow, there has been an ongoing search for increasing water efficiencies, and the use of appropriate variables that relate the supply of irrigation water with the consumptive use of this water, as well as the benefits gained from this supply and use. The oldest of these variables is irrigation efficiency (IE). First coined in the 1950s (Israelson, 1950; Jensen, 2007), it stems from studies of water applied to and consumed from the soil root zone first described as field application efficiency (e_a) (Israelson et al., 1944). However, with the rapid increase in irrigation construction after World War 2, IE, the ratio of water consumed to that diverted or applied, quickly became a factor in engineering to use in design of irrigation technology and operations. It has gained a new field of use from the 1990s in irrigation performance studies and basin water accounting (Seckler, 1996; Lankford, 2006). Since the 1990s, there has also been a shifting focus on productivity, which goes beyond the scale and perspective of irrigation alone. These interests in water productivity (WP) take on 'global' and cross-sectoral concerns, viewed at the basin or resource scale. This paper sets out to unravel the concepts and notions of efficiency from productivity, and irrigation engineering perspectives from multiple use perspectives.

We argue that this emphasis on technical perspectives and what criteria are the most appropriate at which scale of analysis, provides additional insights and structure to critiques on efficiency studies already done for water resources planning (Seckler et al., 2003; Perry, 2007), and improves understanding for scientists modeling agricultural water productivity (Bluemling et al., 2007). Three sections follow that in turn examine: (a) the shifting uses of IE in engineering studies; (b) different approaches to studying water productivity and problems arising in their operational use; and (c) non-fertile crossbreeds emerging between these concepts through notions of water use efficiency that tend to confound productivity gains with efficiency gains. The merits and limitations of each of these notions are discussed with the aim of delineating their utility in demarcated contexts and scales in resolving specific irrigation and water management questions. We argue that the notion of water productivity is the most suited to address the multifaceted context of multiple uses at the river basin scale, through its specific application in building 'water productivity mosaics'.

Both efficiency and productivity terms are nowadays widely applied, frequently outside the original contexts for which they were initially defined, at different scales and comparatively in ways never intended originally. This is often done with political and social purposes in mind. Thus efficiency factors can be taken up by engineers in comparative performance studies to justify modernization programmes (Kahlown et al., 2006). Scientists of various fields may show that irrigation users thought wasteful at local scale can be seen as more efficient at basin scale (Guillet, 2006; Clark and Aniq, 1993; Molden and Sakthivadivel, 1999), or comparative

* Corresponding author.
E-mail address: Gerardo.vanHalsema@wur.nl (G.E. van Halsema).

0378-3774/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2011.05.016

studies of water use are framed in 'good' and 'poor' performers (Molden et al., 1998). On the other hand, concerns arise with misuse of the water productivity concept, when, often with the aim of providing a new 'social' mandate for irrigation, engineers and scientists argue the need to improve the productivity of irrigation water. Frequently water productivity is imbued with a persistent engineering efficiency perspective, rather than productivity *per se*, when it is argued that water savings are possible while maintaining and increasing yields, and making savings available for other uses. This argument confuses 'dry' with 'wet' water savings, when efficiency gains lead to reallocation of water use rather than true water savings of the resource base in the basin (Seckler, 1996).

It is the social claims made around studies of irrigation efficiency or agricultural water productivity, to support new public action and new policies, which make them relevant to study through political ecology perspectives that focus on the allocation and regulation processes governing natural resources management. However, in this paper we stay focused on the confusions in terminology in place, to encourage better discussion of practical water management options. We argue that practical needs and decisions are better served by keeping the contextual relativism of IE and WP clear. More confusion and scope for abuse comes from general absolutism, where comparative data is scrutinized in relation to supposed good norms argued to be scientifically derived and neutral.

2. Irrigation efficiency and agricultural engineering traditions

The notion and concept of irrigation efficiency – defined as the ratio IE = [water beneficially used]/[total water applied] – is the traditional concept of efficiency in irrigation engineering (Israelson, 1950; Jensen, 2007). It focuses on the amount of water released from a source to ensure beneficial uses are achieved – both in terms of water consumption by crops and, more recently, allowances for agronomic needs such as leaching (Burt et al., 1997). In line with its predecessor *irrigation duty* (Buckley, 1920), IE provides a measure of the overall functioning of irrigation. Where high duties and efficiencies are deemed desirable and indicators of good performance, low efficiencies indicate room for improvement. The attractiveness of IE subsequently lies embedded in its constituent parts that distinguish conveyance efficiencies (e_c) from application efficiencies (e_a). This neatly distinguishes the irrigation engineering/management efficiency from the farmer/agronomic efficiency.[1] It provides thereby a demarcated focus on water 'losses' that may occur within the irrigation "engineering" domain in conveying a given amount of water from A to B (Bos and Nugteren, 1982). Conveyance efficiencies, as indicators of how much water is needed to deliver water, can then be regarded as 'classical engineering efficiencies' (Perry, 2007).

This does, however, not hold true for the application efficiency component, where water changes from object to subject of transformation when passing from irrigation canals (conveying water) to farm (growing crops) (van Halsema, 2002). IE thus becomes 'contaminated' with an indicator of efficacy (see next section) that introduces complications and scope for confusion of interpretation. This has led to numerous adaptations of formulae for IE for farm/plot level that introduce complications in the definition of [beneficial use]. These definitions can be subjected to farmers', agronomist's and soil-chemist's perspectives and values, on top of the traditional irrigation engineering definition (Burt et al., 1997; Keller and Keller, 1995).

As succinctly argued by Perry (2007), the widespread application of IE and its associated terminology of water losses can provide a false sense of water wasted. We argue that IEs are defined from a proprietor's perspective – e.g. the allocated water belongs to (or, is associated with) the irrigation system, and IEs provide a measure of how well the system handles/uses this water and is able to convey it without 'waste' (efficiency component) and convert it to productive use (efficacy component). The water leaving the system's management/engineering domain is subsequently regarded as a loss to the proprietor. [2]

However, once we shift perspective to the river basin, 'wasted water' is (in the majority of cases where there is no direct outflow to the sea) used elsewhere in the basin/aquifer for multiple other purposes and productive uses. So, rather than being wasted, water is left unutilized for other people/purposes.[3] If subsequently such 'wasted' fractions of irrigation water are recaptured for utilization within the irrigation scheme this frequently, especially in closed river basins (Molle et al., 2010; Seckler, 1996), leads to depletion of water resources downstream. Thus in effect, resulting in a reallocation of water from downstream use(r)s (back) to the irrigation scheme (Molden, 1997; Molden and Sakthivadivel, 1999; Seckler et al., 2003; Guillet, 2006; Lankford, 2006; Perry, 2007). This generally has the overall result that production and water consumption (i.e. ET) increase, as well as the overall scarcity and competition for water resources in the river basin. Thus, where effective improvements in IE may suggest significant efficiency gains at the level of the irrigation scheme, they essentially equate to the appropriation of water by asserting irrigation claims on the water resources base, as expressed in the gross water allocations or permits.

In principle 'good' or preferred practices are feasible when improved IEs diminish irrigation's gross water intake and water consumption in accordance with the implied efficiency gains (Lankford, 2006). However, these often prove difficult to establish and implement (van Halsema et al., 2011). Moreover, these require the re-assessment and deliberation of water resources allocation that cannot be genuinely informed in the absence of hydrological water accounting at the basin level (Molden, 1997; Perry, 2007). IEs are too limited in their scope and purpose in this regard, if their 'wasted' fraction is not verified against actual reuse by other uses and users in the basin.

When applied at the scale of irrigation schemes, classical IEs have become indicators for, and measures of performance of, irrigation technology (Brouwer et al., 1989; Bos and Nugteren, 1982; Kahlown et al., 2006). For example, the following ranges are common estimates in text books that are widely applied for design and calculation of gross water allocations:

- Open channel – surface irrigation schemes 30 < IE < 60
- Modern irrigation (open-closed) 50 < IE < 70
- Trickle irrigation system 70 < IE < 90

As such they have frequently been applied to indicate poor performance of irrigation schemes, followed by quick recommendations for technological upgrades or irrigation modernization – e.g. increase performance by increasing IE, improve water deliv-

[1] Strictly speaking this is not a neat divide, as the agronomic performance of crop production and water consumption is influenced not only by the quantity of water but also by its timing, which falls under the irrigation operator's management domain of irrigation scheduling.

[2] This proprietor's perspective is probably as much informed by the investor's perspective – irrigation systems traditionally require huge capital outlay, especially in relation to canal carrying capacities, which one would wish to optimize in terms of conveyance efficiency. Similarly, a climate perspective may inform the improvement of IE to save energy, when irrigation water is supplied by pumping.

[3] Exceptions to rule are non-utilized water flows that seep into poor quality water sinks (e.g. saline aquifers) that render their further utilization impossible or non-productive – e.g. non-recoverable flows.

ery capacity by capturing 'wasted water' (for example as with canal lining or closed pipe conveyance) and delivering it on farm.

However, IE are performance measures of technology and not of the system – they indicate the water conveyance efficiency of the infrastructure, and not of the water delivery efficiency and efficacy of irrigation operation and maintenance (O & M) – which is further affected by the effective control and timely scheduling of water distribution.

There are two reasons why irrigation efficiencies remain popular among irrigation engineers, but also still bring problems if misused. First, IEs are engineers' technological fixes (and fixations) to mitigate institutional limitations in implementing O & M according to designed principles and/or matching actual irrigation water requirements. For example, too frequently tail end problems are targeted to be solved by attempts to capture 'wasted' fractions of IEs, without attempting to tackle the higher level impact of skewed water delivery practices (e.g. canal lining in Pakistan, see Kahlown et al., 2006). Secondly, IEs are widely used as design parameters for irrigation design and lay-out, where conveyance efficiencies by type of canal segments are taken from textbooks. Allowing for generous 'losses' at the design stage, may thus permit for technological fixes, and re-appropriations of 'wasted' fractions, at a later stage.

IEs are less transparent than implied and frequently used, as they are scale dependent, both in time and space – this hampers comparison of IE values, across scales, time-frames and localities. Moreover, as with the introduction of the river basin focus now occurring, switching scales can drastically turn around the attributed performance value of IE from poor (30%) to good (80%), as initially regarded 'wasted fractions' become beneficially 're-used' (Clark and Aniq, 1993; Guillet, 2006).

Beyond engineering traditions, other scientists have come in to argue, criticise and calculate IEs, especially at farm and field level. While the original use of the term irrigation application efficiency began at crop level, real measurements of field and farm-level IEs have proved very difficult to assess (Jensen, 2007), and figures of IE remain most diverse and least specific at this level. Thus, there are very different views of what constitutes 'beneficial use' subject to farmers', agronomist's and soil-chemist's perspectives on top of the irrigation engineering, and a large range of values of IEs can be found (Burt et al., 1997; Keller and Keller, 1995).

Trying to adapt these definitions and formulae, especially to enable shifts between scales (and thus perspectives), is deemed unhelpful. We argue that it is better to limit the use of IEs to its constituent components of conveyance efficiencies (primary, secondary, tertiary) and application efficiency (plot, farm), where they can attribute clear value to the specific technological function of irrigation components (van Halsema et al., 2011) – no more, and no less.

For performance studies of irrigation systems we argue it is better to use variables that characterize the delivery of water in ways that can be related to institutional conditions as much as technology. In particular the Relative Water Supply (RWS) or Relative Irrigation Supply (RIS) – [volume of water delivered]/[actual crop water requirements] – provides a succinct indication of the overall efficacy (or adequacy as more commonly referred) of irrigation (Levine, 1982; Rodriguez-Diaz et al., 2008). In combination with the classical IE, the efficiency of water delivery technology and its effects on adequacy can be assessed and pinpointed at different scales of the system (e.g. system, primary, secondary and tertiary level). In addition, however, the RWS also provides an indication for the physical need and social willingness to invest in and perform a tight water management control through institutional water management arrangements (Levine, 1982; van Halsema, 2002; van Halsema et al., 2011).[4] Similarly, the Delivery Performance Ratio (DPR) – defined as the ratio of [actual discharge]/[target discharge] – provides a measure of performance of the quality (or efficacy) of water delivery service throughout an irrigation scheme (Murray-Rust and Snellen, 1993; Murray-Rust and van Halsema, 1998; Vos and Vincent, 2010). Besides indicating the scope within a system to avoid tail-end problems through improved operational water management, DPR also permits an assessment of the scheduling practices. This latter is important in relation to the timeliness and adequacy of water delivery, as this affects actual crop production, its beneficial water use and thus eventual IE.

For performance assessments within the demarcated scale of irrigation command areas the classical notions of IE, RWS and DPR are well suited. Especially in their combined use and application at different spatial (e.g. primary, secondary, tertiary level) and time (e.g. weekly, seasonal, yearly) scales, they are useful instruments to characterize both efficiency and efficacy of irrigation – in terms of both technological and institutional irrigation water management. They are, however, restricted to the irrigation objectives as encapsulated in the proprietor's perspective of water allocation utilization. The relation and impact of irrigation's water use at basin level falls outside the scope and merit of these classical irrigation notions. We propose this remains so, and that the IE and associated notions are not used in basin level water resources studies. For the latter, water productivity is more appropriate.

3. Water productivity – the producers domain

The notion and concept of Water Productivity (WP) – defined here as the ratio (or unit) WP = [product]/[water consumed] – is regarded as increasingly important. It provides a notion, and attributes a specific value, of the productivity of water that can be optimized in times and localities of increasing absolute and relative water scarcity. Producing '*more crop per drop*' (Giordano et al., 2006; FAO, 2002; Kassam et al., 2007) remains a widely used mantra for the (irrigated) agricultural sector that is informed by the notion of WP – e.g. increase the benefits (products) obtained per unit of water consumed. This objective has been informed by the traditionally low irrigation efficiency performances, below optimal yield production levels per ha (e.g. the yield gap) and increasing water scarcities at river basin scale. Increasing the WP of irrigated agriculture is thereby seen as the critical element in increasing agricultural production without major increases in fresh water diversion to agriculture (de Fraiture et al., 2010; de Fraiture and Wichelns, 2010; Molden et al., 2010). However, considerable confusion and questionable inductions occur when the definition and value of the denominator [water consumed] is confused with that of *water diverted, delivered, applied*, etc. This latter 'abuse' of the concept of WP again introduces notions of irrigation and water use efficiencies (WUE) (see next section), that are scale dependent and informed by the proprietors' principle of water use. These tend to hide rather than explain the potential trade-offs and reallocations of water uses and users in a water scarce basin when increases in agricultural production are propagated (see examples provided by Perry (2007)). To avoid these confusions in future, we argue that the notion of WP should be defined with the denominator as [water consumed].

When crop production processes are defined in terms of WP = [yield or biomass]/[(evapo)transpiration] – either in kg m^{-3} or kg kg^{-1} – the concept indicates the efficacy of these crop production processes in relation to their required water consumption. Unfortunately, and rather confusingly, this measure of produc-

[4] E.g. high RWS values take away the incentives for tight water management and investments in high efficiencies.

tivity has a long tradition among crop physiologists which they continue to call water use efficiency (WUE) (*see* Bluemling et al., 2007; Perry, 2007). From the irrigation perspective, however, WUE should be reserved for gross water applications (see next section) and WP for actual water consumed. WP is then an efficacy parameter of the crop production process, where water (as well as other inputs) is subject to a transformation process of crop or biomass production, owned and managed by the farmer. In contrast, WUE or IE, are then reserved for efficiency parameters of the irrigation.

Crop water productivity is governed by the crop growth and production parameters, rather than by irrigation parameters. Physiologically the water consumption (transpiration) and assimilation (biomass, yield) processes of crops are strongly linked, as both depend on the plant stomata. The values of crop WP are thereby primarily determined by: (i) crop type and crop genetics (e.g. C3, C4, HYV, etc.); (ii) nutrient deficiencies in the crop growth cycle (e.g. nutrient deficiencies equate to lower WP), and (iii) to a lesser extent, irrigation application and cultivation techniques that affect evaporation (Steduto et al., 2007; de Wit, 1958).

Improvements in WP are thus primarily achieved by increasing the value of the benefit in relation to the water consumed – e.g. on the plant production side, or producers' water users' domain. Foremost these are related to agronomic practices that determine crop choices, and nutrient and pest management. True gains in WP are those where yield increases are achieved without increases in evapotranspiration, or where the non-beneficial evaporation is reduced through practices as mulching and localized irrigation while maintaining or increasing production and transpiration levels. These can be considered as productivity gains that do not affect the total water use (whether at field, irrigation scheme or river basin level). Another element concerns then the management of (irrigation) water in relation to its *timing*, rather than quantity. Here the commercial yield fraction of the crop (yield = HI * Biomass) (where HI is the Harvest Index) may be improved or kept high by avoiding crop water (transpiration) stresses during the critical periods of yield formation (Wheeler et al., 1996; Oweis et al., 2000; Benli et al., 2007). Whereas the biomass correlates linearly to the (evapo)transpiration for any given crop/nutrient level, the HI is highly sensitive to periodic water stress. For example, for any total ET the total biomass will be the same, but the yield may be considerably higher for non-water stressed yield formation than for stressed ones. Strictly speaking total crop water consumption (actual evapotranspiration), and hence biomass, will vary with water stress due to stress induced canopy growth retardation (Ben-Gal et al., 2010) and phenologic (crop maturity) acceleration (Benli et al., 2007; Stockle et al., 1997).

A big advantage of the WP parameter is that any absolute increase in water consumption monitored equates unequivocally with an absolute increase in water depletion within the hydrological domain.[5] This immediately implies any increase must be accounted for in terms of: (i) from where (rainfall, irrigation scheme (or 'wasted' fraction), aquifer, etc.) and (ii) from whom/what (the ecological base flow, drainage effluent, groundwater recharge, etc.) it is derived. This forces explicit consideration of any increase or decrease in water consumption in terms of a re-allocation of actual water use within the hydrological domain.

Although strictly speaking crop WP is determined at the (plant) production system level, WP values can be compared across time and geographical scales (Zwart and Bastiaanssen, 2004; Sadras and Angus, 2006). Variations of WP among production systems (say wheat) provide indicative and quantifiable opportunities to raise low productivity levels to established high levels through adaptation of the production system. These variations provide indications of potential productivity gains without increasing water depletion/consumption[6] that go at the expense of someone/something else.

The notion of WP can also be applied in a wider sense, by attributing different values to the [product] in the numerator. This is commonly done in water valuation approaches, where economic attributes can be given in monetary terms [$\$.m^{-3}$]; social attributes [jobs, food security, etc.], or environmental attributes [carbon sequestration, biodiversity, etc.] (Turner et al., 2004; Knox et al., 2000; Renault and Wallander, 2000). The attractiveness of economic valuation is that it provides a method to compare (or even add – though not recommended (see Hermans et al. (2006a)) – economic WP values not only across scales, but also across production systems (crops, energy, fisheries, livestock, etc.). Economic water productivity thus provides a tool to attribute value and productivity to all water uses and users within a hydrological domain, and not only those pertaining to the irrigated agriculture. When based on hydrological accounting of actual water consumption, a value (whether economic, social, ecological or agronomic) can be attributed to all water uses and re-uses, including those tend to be left unaccounted for in IE approaches as 'wasted fractions' non-utilized by irrigation.

The potential pitfalls of this approach, however, are:

1. Economic WP values do not necessarily equate to crop-WPs: e.g. high value cash crops versus low value staples – maximum net income may be achieved at lower levels than maximum yield productivity.
2. Economic WP values are susceptible to the vagaries of the markets and economy, which are typically contextually bounded (Hermans et al., 2006a).
3. Methodological complications arise for extension of WP to non-consumptive production processes such as hydropower, fisheries (and biodiversity to some extent) and recreation.
4. Additional benefits of irrigation for other agronomic activities (e.g. aiding harvesting, frost protection, disease control, etc.) which are not directly part of increasing yield and crop value tend to remain un-assessed.
5. Additional water valuation methods need to be deployed to capture broader societal benefits of water use (e.g. jobs, food security, poverty reduction, etc.).

On the other hand, it provides a powerful tool to attribute value to water bodies and quantities that are traditionally regarded as 'unutilized' resources.

4. Water use efficiency – a non-fertile cross breed

From the irrigation and water management perspective the notion of Water Use Efficiency (WUE) is introduced as a combination of the efficiency and productivity ratios. WUE is generally defined as: WUE = [product]/[water applied/available] – e.g. $kg\,m^{-3}$ or $kg\,kg^{-1}$. The denominator [water applied] usually taken as irrigation water plus rainfall. *Water applied* in this sense represents the ***gross*** amount of water availability at field level,[7] of which an undetermined fraction equating to actual crop evaptotranspiration

[5] E.g. when increased production (and water productivity) in rainfed agriculture is achieved, as currently widely attempted, the resulting diminished replenishment of aquifers and rivers can be assessed by quantifying the resulting increase in actual evapotranspiration of these improved agricultural practices.

[6] Or with minimal relative, but quantifiable, increase only.

[7] Confounding the confusion and problems further, frequently *water applied* is defined in terms of ***gross*** water availability at irrigation scheme level, rather than field level. This further diminishes its value as all conveyance losses are then

(ET_a) is actually utilized for the crop physiological conversion process of biomass production and yield formation. WUE calculated in this crude manner thus represents an efficiency parameter of water utilization at farm/plot level, with all the scale and context specific limitations of the classical IE. The notion of WUE is informed by the need to maximize the production per unit of available water in times of increasing food requirements and limited available water resources (de Fraiture et al., 2010; de Fraiture and Wichelns, 2010; Molden et al., 2010). WUE thereby seems intended as a measure of productivity of provided water, but in effect is a measure of efficiency whereby low values again provide a false sense of "wasted" water.

The principal problem with the widespread use of WUE, however, is its haphazard application to various components of the water balance (*cf.* Bluemling et al., 2007; Perry, 2007), which makes its utility as a comparative measure of efficiency (or productivity) null and void. From a crop physiological perspective, what has been coined as WUE_{crop} or WUE_{ET} (Bluemling et al., 2007; Sadras and Angus, 2006) should effectively equate to our definition of WP = [production]/[sum of ET_a] ($kg\,m^{-3}$ or $kg\,kg^{-1}$). The haphazard use of WUE, however, is induced by the methodological difficulties in measuring and accounting accurately for actual evapotranspiration (ET_a) through water balance approaches. Frequently ET_a is calculated as the remainder value of the water balance: $ET_a = I + P - R - D - \Delta S$[8] – often with further introduction of simplified conditions that lead to assumptions of runoff (R) and drainage (D) values equating to zero. Evapotranspiration is thereby equated to the sum of irrigation and rainfall minus the change in seasonal soil moisture storage. This, however, assumes that all irrigation and rainfall water (when considered at field level) is effectively stored in the root zone and accounted for in evapotranspiration or change in soil moisture. Without effective accounting of these water balance components through, for example, accurate measurements by high frequency neutron probe measurements, lysimeter measurements and ET_a modeling, these assumptions frequently do not hold true. Failure to account for runoff and deep percolation of irrigation and/or rainfall may lead to gross overestimations of actual evapotranspiration (ET_a) when these effects are mistakenly subsumed in the periodic measurement of change in soil moisture content (ΔS) (Oktem et al., 2003; Kamilov et al., 2002). Underestimations of ET_a occur when the ΔS is not accounted for accurately in trials of deficit irrigation (Sun et al., 2006). In a review of 24 recent publications on WUE studies of wheat, maize and rice only 7 publications provided enough data to reconstruct the water balance – of these, only 2 publications provided for a water balance in which the actual evapotranspiration could be correctly accounted for. Thus 22 of these 24 publications provided WUE values that are measures of gross water use efficiency, without accounting for which fraction of the total *water applied* is actually utilized for crop evapotranspiration and production (van Halsema unpublished, ongoing). WUE is thereby subjected to the same limitations as IE, in that it becomes a scale and context dependent measure of water efficiency, and its values are therefore no longer comparable across applications. Any suggested improvements in WUE, when affecting the denominator [water applied] go at the expense of someone, something and somewhere else within the hydrological domain. They are not a measure of productivity increase but of localized efficiency and basin scale water re-allocation.

To avoid further confusion and inappropriate comparisons of values, we strongly argue to reserve the concept of WP as a measure of productivity of the crop physiological process of biomass production and yield formation related to actual crop water consumption (WP = [kg product]/[ET_a]), where the value of ET_a is accurately accounted for. The notion of WUE, as a measure of efficiency like IE, should then be reserved for any measure of gross water application/availability for crop production that may be purposely accounted for, or stem from methodological and measurement limitations. As a true measure of productivity, only WP can be compared across scales, geographies and applications when applied to the same class of crops. Combining WP with WUE will thereby yield the application efficiency of irrigation, or effective fraction of precipitation (WUE/WP = e_a).

5. Building WP mosaics of multiple water (re)uses at basin level

Water valuation methods are moving beyond economic attributes only, especially in studies of integrated water resources management (IWRM) (Turner et al., 2004; Hoekstra et al., 2001). Emphasis has been put on developing new practical tools that include social and environmental values alongside economic ones, with the hope to integrate practical feasibility, analytical integrity and policy relevance (Turner et al., 2004; Burill, 1997; Sullivan and Meigh, 2003; Daily et al., 2000; Hermans et al., 2006b).

On the one hand these social and environmental values are drawn up from stakeholder consultations and interviews. Thus locally derived value attributions to the numerator of WP (see above) are defined to qualify and/or quantify the social, ecological and economic value of water use. This also enables local prioritization of value attribution, and valuation from economic and environmental perspectives, – although there is more work needed on methodologies for assessing environmental values (see pitfalls of WP above) (Hermans et al., 2006a; Daily et al., 2000).

On the other hand, water valuations based on the WP denominator are generally based on thorough methods to account for water across a basin (or hydrological sub-unit). These use and require good water balance studies to map net (or actual) water consumption across an area by different water use(r)s. By explicitly targeting and mapping all (multiple) water uses in a hydrological domain, unutilized water fractions do not need to be accounted for at the individual scale of water use (say irrigation scheme). These can be discarded as replenishment of the water resources base at the hydrological scale. Thus, a mosaic of WP values can be built up at the hydrological scale, without having to worry about local water diversions or reuses.

Subsequent analysis of the individual WP values in the mosaic – both among similar water uses and across different water uses – enable a focused deliberation of how to improve water productivity in the hydrological domain. It quantifies and qualifies the potential to raise the productivity of low value water use cells to those of similar water use high value cells; or, to transform low value water uses into high economic water uses. If analysis of economic conditions suggests water consumption will increase, WP mosaics may indicate where this water may need to come from (e.g. upstream use(r)s, nature, fisheries, aquifer) and what social and political dynamics might be involved. Only after thinking about what reallocation might be necessary may it be relevant to analyse local IE information (Hermans et al., 2006a).

6. Conclusions

Since the 1940s, the interests of study in irrigation efficiency have moved from studying water application, through irrigation

attributed to the low productivity without accounting for its potential re-use downstream.

[8] With I = irrigation water application, P = rainfall, R = runoff, D = drainage or deep percolation and ΔS change in soil moisture content, G = (if applicable) groundwater contribution.

system design and operation into system performance evaluation and basin water accounting. In these shifts, variables which once had a specific contextual meaning have become related to the economic and social context of the study of water use. They can also be related with how groups of people make claims and steer policies to justify or transform water use for users and the environment. It is this political use of factors, that are derived and also often portrayed as neutral, that makes them relevant to study under the frame of political ecology. In this paper, we show how conscientious scientific and engineering practice can avoid misuse of figures and notions that are increasingly questioned by political ecology, as they can influence political, economic, and social dynamics of water use that can also affect environmental issues.

Our conclusion is that contextual relativism is better than general absolutism in analyses for managing water for productivity – one notion and certain figures will not fit all. We have argued three key methodological guidelines for managing water for productivity.

1. Do not use engineering notions with rigid definitions outside their specific demarcated scales – but use them effectively and properly at these scales. Limit the use of IEs to their constituent components of conveyance efficiencies (primary, secondary, tertiary) and application efficiency (plot, farm), where they can attribute clear value to the specific technological function of irrigation components – no more, and no less.
2. For water management, better guidance comes from mapping out diverse notions and values of water use efficiency and productivity factors within scheme, at scheme and catchment scale. This is what enables identification of opportunities and potential conflicts from changing water uses, the resulting trade-offs in allocations, and realism in ideas for institutional and technological change. This provides a way of looking at water without a 'proprietors' perspective. If there are to be changes in uses and users, such water productivity mosaics can start to show the implications of changing allocations and appropriations of water resources. A focus on WP enables real thought about both the numerator and the denominator, on the production side and on the water utilization side, and what values to attribute to the numerator depending on the perspective one takes.
3. Showing a mosaic of water values in a basin is a suitable tool to map out the options for all uses in agriculture and environment, and not only irrigation. Doing this is more transparent for public action, as most of us, including political ecologists, would like.

References

Ben-Gal, A., Kool, D., Agam, N., van Halsema, G.E., Yermiyahu, U., Yafe, A., Presnov, E., Erel, R., Majdop, A., Zipori, I., Segal, E., Ruger, S., Zimmermann, U., Cohen, Y., Alchanatis, V., Dag, A., 2010. Whole-tree water balance indicators for short-term drought stress in non-bearing 'Barnea' olives. Agric. Water Manage. 98, 124–133.
Benli, B., Pala, M., Stockle, C., Oweis, T., 2007. Assessment of winter wheat production under early sowing with supplemental irrigation in cold highland environment using CropSyst simulation model. Agric. Water Manage. 93, 45–53.
Bluemling, B., Yang, H., Pahl-Wostl, C., 2007. Making water productivity operational – a concept of agricultural water productivity exemplified as a wheat–maize cropping pattern in the North China Plain. Agric. Water Manage. 91 (1–3), 11–23.
Bos, M.G., Nugteren, J., 1982. On Irrigation Efficiencies Int'l Inst. for Land Reclamation and Improvement, 3rd edition.
Brouwer, C., Prins, K., Heibloem, M., 1989. Irrigation Water Management: Irrigation Scheduling. Training Manual No. 4. FAO, Rome.
Buckley, R.B., 1920. Irrigation Pocket Book, or Facts, Figures and Formulae for Irrigation Engineers, 3rd edition. E & FN Spon Ltd., London.
Burill, A., 1997. Assessing the Social Value of Water and its Uses, Inst. for Prospective Technological Studies. Joint Research Centre of the European Commission, Sevilla, Spain.
Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Eng. (November/December), 423–442.
Clark, A.K., Aniq, M., 1993. Canal irrigation and development opportunities for the Indus Right Bank in Sindh and Balochistan. ICID Bulletin, vol. 42 (1), pp. 11–32.
Daily, G.C., Soderqvist, T., Aniyar, S., Arrow, K., 2000. The value of nature and the nature of value. Science 289, 395–396.
de Fraiture, C., Wichelns, D., 2010. Satisfying future water demands for agriculture. Agric. Water Manage. 97, 502–511.
de Fraiture, C., Molden, D., Wichelns, D., 2010. Investing in water for food, ecosystems and livelihoods: an overview of the comprehensive assessment of water management in agriculture. Agric. Water Manage. 97, 495–501.
de Wit, C.T., 1958. Transpiration and crop yield. Versl. Landbouwk. Onderz. 64.6 Inst. of Biol. and Chem. Res. on Field Crops and Herbage, Wageningen, the Netherlands.
Food and Agriculture Organization (FAO), 2002. Crops and Drops: Making the Best Use of Water for Agriculture. FAO, Rome.
Giordano, M., Rijsberman, F., Maria Saleth, R. (Eds.), 2006. 'More Crop per Drop': Revisiting a Research Paradigm. IWA Publishing House, UK.
Guillet, D., 2006. Rethinking irrigation efficiency: chain irrigation in Northwestern Spain. Hum. Ecol. 34 (3), 305–329.
Hermans, L.M., van Halsema, G.E., Mahoo, H.F., 2006a. Building a mosaic of values to support local resources management. Water Policy 8, 415–434.
Hermans, L.M., van Halsema, G.E., Renault, D., 2006b. Developing economic arrangements for water resources management – the potential for stakeholder oriented water valuation. In: Water and Agriculture: Sustainability, Markets and Policies , OECD, Paris, London. IWA Publishing, pp. 280–303.
Hoekstra, A.Y., Saveneije, H.H.G., Chapagain, A.K., 2001. An integrated approach towards assessing the value of water – a case study on the Zambezi basin. Integr. Assess. 2, 199–208.
Israelson, O.W., 1950. Irrigation Principles and Practices. Wiley, New York.
Israelson, O.W., Criddle, W.D. Furriman, D.K., Hansen, V.E., 1944. Water application efficiencies in irrigation. Agr. Exp. Stn. Bull. 311. Utah State Agr. College, USA.
Jensen, M., 2007. Beyond irrigation efficiency. Irrig. Sci. 25, 233–245.
Kahlown, M.A., Khan, A.D., Azam, M., 2006. The world's largest contiguous irrigation system – developments, successes and challenges of the Indus irrigation system in Pakistan. In: Tvedt, T., Jakobsson, E. (Eds.), A History of Water Vol. 1: Water Control and River Biographies. I.B. Taurus, London, pp. 35–54.
Kamilov, B., Ibragimov, N., Evett, S., Heng, L., 2002. Use of neutron probe for investigations of winter wheat irrigation scheduling in automorphic and semi-hydromorphic soils of Uzbekistan. In: Proceedings of the International Workshop on Conservation Agriculture for Sustainable Wheat Production in rotation with Cotton in limited water resource areas , Tashkent, Uzbekistan, October 13–18.
Kassam, A.H., Molden, D., Fereres, E., Doorenbos, J., 2007. Water productivity: science and practice – introduction. Irrig. Sci. 25, 185–188.
Keller, A., Keller, J., 1995. Effective efficiency: a water use efficiency concept for allocating freshwater resources. Water Resources and Irrigation Division, Discussion Paper 22, Winrock International, USA.
Knox, J.W., Morris, J., Weatherhead, E.K., Turner, A.P., 2000. Mapping the financial benefits of sprinkler irrigation and potential financial impacts of restrictions on abstractions: a case-study in Anglian Region. J. Environ. Manage. 58, 45–59.
Lankford, B., 2006. Localising irrigation efficiency. Irrig. Drain. 55, 345–362.
Levine, G., 1982. Relative water supply: an explanatory variable. In: Technical note 1, the determinants of developing country irrigation problems project, Cornell and Rutgers University, Ithaca NY.
Molden, D., 1997. Accounting for Water Use and Productivity. SWIM Paper 1. International Water Management Institute (IWMI), Colombo, Sri Lanka.
Molden, D., Sakthivadivel, R., 1999. Water accounting to assess use and productivity of water. Int. J. Water Resour. Dev. 15 (1/2), 55–77.
Molden, D., Sakthivadivel, R., Perry, C.J., de Fraiture, C., Kloezen, W.H., 1998. Indicators for comparing performance of irrigated agricultural systems. Res. Rep., vol. 20. International Water Management Institute (IWMI), Colombo, Sri Lanka.
Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: between optimism and caution. Agric. Water Manage. 97, 528–535.
Molle, F., Wester, P., Hirsh, P., 2010. River basin closure: processes, implications and responses. Agric. Water Manage. 97, 569–577.
Murray-Rust, D.H., Snellen, W., 1993. Irrigation System Performance: Assessment and Diagnosis. International Irrigation Management Institute (IIMI), Colombo, Sri Lanka.
Murray-Rust, D.H., van Halsema, G.E., 1998. Effects of construction defects on hydraulic performance of Kalpani distributary, NWFP, Pakistan. Irrig. Drain. Syst. 12 (4), 323–339.
Oktem, A., Simsek, M., Gulgun-Oktem, A., 2003. Deficit irrigation effects on sweet corn (*Zea masy sacharata* Sturt) with drip irrigation system in a semi-arid region. I Water-yield relationship. Agric. Water Manage. 61, 63–74.
Oweis, T., Zhang, H., Pala, M., 2000. Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean environment. Agron. J. 92, 231–238.
Perry, C., 2007. Efficient irrigation; inefficient communication; flawed recommendations. Irrig. Drain. 56 (4), 367–378.
Renault, D., Wallander, W.W., 2000. Nutritional water productivity and diets. Agric. Water Manage. 45 (3), 275–296.
Rodriguez-Diaz, J.A., Camacho-Poyato, E., Lopez-Luque, R., Perez-Urrestarazu, L., 2008. Benchmarking and multivariate data analysis techniques for improving the efficiency of irrigation districts: an application in Spain. Agric. Syst. 96, 250–259.
Sadras, V.O., Angus, J.F., 2006. Benchmarking water-use efficiency of rainfed wheat in dry environments. Aust. J. Agric. Res. 57, 847–856.
Seckler, D., 1996. The new era of water resources management: from 'dry' to 'wet' water savings. Res. Rep. vol. 1, International Irrigation Management Institute, Colombo, Sri Lanka.

Seckler, D.D., Molden, R., Saktivadivel, 2003. The concept of efficiency in water-resources management and policy. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities. CAB International, Wallingford, UK, pp. 37–51.
Steduto, P., Hsiao, T.C., Fereres, E., 2007. On the conservative behavior of biomass water productivity. Irrig. Sci. 25, 189–207.
Stockle, C.O., Cabelguenne, M., Debaeke, P., 1997. Comparison of CropSyst performance for water management in southwestern France using submodels of different levels of complexity. Eur. J. Agron. 7, 89–98.
Sullivan, C., Meigh, J., 2003. Considering the water poverty index in the context of poverty alleviation. Water Policy 5 (5–6), 513–528.
Sun, H.Y., Liu, C.M., Zhang, X.Y., Shen, Y.J., Zhang, Y.Q., 2006. Effects of irrigation on water balance, yield and WUE of winter wheat in the North China Plain. Agric. Water Manage. 85, 211–218.
Turner, K., Georgiu, S., Clark, R., Brouwer, R., Burke, J., 2004. Economic Valuation of Water Resources in Agriculture. From the Sectoral to a Functional Perspective of Water Resources management. FAO Water Reports 27, FAO, Rome.
van Halsema, G.E., 2002. Trial and re-trial: the evolution of irrigation modernization in NWFP, Pakistan. Ph.D. thesis, Wageningen University, The Netherlands.
van Halsema, G.E., Beshir Keddi Luncha, Mengitsu Assefa, Hengsdijk, H., Wesseler, J., 2011. Performance assessment of smallholder irrigation in the Central Rift Valley of Ethiopia. Irrig. Drain., doi:10.1002/ird.613.
Vos, J., Vincent, L., 2010. Volumetric water control in a large-scale open canal system with many smallholders: the case of Chancay-Lambeyeque in Peru. Agric. Water Manage. 98 (4), 705–714.
Wheeler, T.R., Hong, T.D., Ellis, R.H., Batts, G.R., Morrison, J.I.L., Hadley, P., 1996. The duration and rate of grain growth, and harvest index, of wheat (*Triticum aestivum* L.) in response to temperature and CO_2. J. Exp. Bot. 47 (5), 623–630.
Zwart, S.J., Bastiaanssen, W.G.M., 2004. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric. Water Manage. 69 (2), 115–133.