Accounting for water use: Terminology and implications for saving water and increasing production

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Accounting for water use: Terminology and implications for saving water and increasing production

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ABSTRACT

Scarcity and competition for water are matters of increasing concern, as are potential shortages of food. These issues intersect both within the agricultural sector and across all water using sectors. Irrigation is by far the largest user of water in most water-scarce countries, and is under pressure to reduce utilisation (to release water to other sectors, including the environment) and use water more productively to meet demands for food and fibre.

The terminology for such intra- and inter-sectoral analysis must be unambiguous across sectors so that interventions and their impacts are properly understood. Such terminology, based on previous work and debate, is set out. Implications for a better understanding of the scope for improved productivity of water in agriculture are traced, and some examples are given using data from recent research submissions, demonstrating the benefits of precise water accounting.

1. Introduction

Concerns about competition for water and the future balance between supply and demand for food are widespread (Easterling, 2007; Molden, 2007). Climate change, at least in some areas, threatens to worsen both problems. In response, the literature, research projects, the activities of research institutes, international organizations and related conferences and workshops are replete with programs, interventions and products designed better to understand, mitigate, and respond to water scarcity and increase the productivity of water in agriculture as well as other sectors.

The issue runs across sectors: foresters, fishermen, recreational users, municipal and rural water utilities, industries, farmers and environmentalists, all have legitimate interests in how water is allocated and used in their own as well as the competing sectors. Language – the terminology of debate – is of central importance to the value that analysis can add to knowledge. Even the most expert discussions can be confused by ambiguous terminology: "effective rainfall" to a hydrologist is the portion of precipitation that contributes to runoff and streamflow. For an agriculturalist, the identical term means the portion of rainfall that contributes to crop water requirements. These two disciplines, then, would collectively identify only deep percolation as "ineffective" – a view that might upset a hydrogeologist.

More generally, the water-dependant sectors have no consistent terminology to distinguish between consumptive and non-consumptive uses or recoverable and non-recoverable return flows.

Thus one can conceive of a representative of each of these sectors sitting around a table; the forester and the rainfed agriculturalist talk about improving their yields per hectare; the irrigation specialist talks about improving efficiency, as does the municipal engineer. The environmentalist (sitting metaphorically in a wetland and waiting for more water) assumes all this will decrease upstream use and improve his area of concern. In fact, the forest and rainfed agriculture improvements will reduce runoff; the improved irrigation will increase the *fraction* of diversions that are consumed, in all probability allowing an increase in irrigated area that will increase *total* consumption; and the increased efficiency of urban use will have almost no measurable effect (recharge to groundwater reduces if leaky pipes are fixed, but diversions from rivers will decline also). So everything "improved" except the wetland, which now is likely drier than before.

Irrigated agriculture is by far the major sector affecting water, though again, all is not so simple in the case of water. Typically some 70% of rainfall evaporates directly or supports local vegetation. Only the remaining 30% contributes to the controllable water supply, such as that diverted to irrigation, municipalities and industries. So irrigation is generally the target for reducing water use, to release it to the cities or to environmental uses. Commonly, irrigation is described as a low value and wasteful use of water (Bhatia and Falkenmark, 1992). It is thus appropriate to start with terminology that can better account for water in irrigated agriculture, and note that the same terminology can be used to assess other sectors, so that the imaginary round-table debate described above

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is conducted in a single language, and that the impacts of proposed interventions are those needed to determine impacts on the hypothetical downstream wetland.

This paper briefly sets out such a set of terms – drawing on those already proposed and discussed by several authors, and recently endorsed by the International Commission on Irrigation and Drainage. Thereafter, the nature of the relationship between water and production in agriculture is explored using this terminology, with examples from recent literature that demonstrate how additional insights are gained by precise, unambiguous accounting.

Finally, conclusions and recommendations are presented, highlighting the importance of adopting strict accounting terms to ensure that lay readers, policymakers, and experts from "other" disciplines are able to understand as fully as possible the nature of the constraint that water scarcity presents, and the potential for interventions to improve matters.

It is also worth stating at the outset that this proposal regarding terminology is not a breakthrough in the struggle to deal with water scarcity or a solution to the problems of food security. Rather it is an approach to improving cross-sectoral understanding of which solutions will work best in particular contexts, and helping researchers better target their efforts. Frequently, the adoption and application of precise water accounting will quickly reveal which options are falsely based on an interpretation of part of the balance sheet rather than the complete accounts.[1]

Following the terminology described here will improve the clarity of research documentation and facilitate the discussion about water competition and the impact of interventions in management or technology.

2. Water accounting: proposed terminology

Some years ago, triggered by the variety of terms used in submissions to the journal Irrigation and Drainage (irrigation efficiency, water saving, efficient water use, water use efficiency, basin efficiency, effective efficiency), ICID embarked on an extensive consultation of its member committees to achieve agreement on a standard set of terms. The consultation was organized around a draft paper that reviewed the literature on the topic starting from the 1940s when Israelsen (1950) first proposed the term "irrigation efficiency" as a measure of the extent to which water diverted from a river or abstracted from a well actually reached the farmer's field and contributed to crop growth. Israelsen's approach was widely adopted and various levels of efficiency were computed (project efficiency, canal efficiency, field efficiency).

The implication of these ratios was that water that did not get from diversion to field, or field to plant, was "lost", and various writers (especially Jensen, 1967, 1993, 2007; Willardson et al., 1994) questioned this notion of losses when viewed from the wider perspective of a basin. The importance of the issue was heightened by two factors. First, the word "efficiency" is value-laden: in all other contexts, an increase in efficiency is "good" – less fuel is consumed per kilometer travelled; less electricity is lost in transmission; less heat is lost from buildings. By contrast, in irrigation the purpose of supplying irrigation water is that it be consumed by the plant because that is a fundamental component of the growth process, and the purpose of improved irrigation technology is to maximise that proportion of water supplied that is consumed by the plant and minimise any return flows to rivers or aquifers. From the farmer's perspective, higher efficiency is good; from the basin perspective, things are not so clear.

The second problem with the efficiency construct derives from the implication that the increase in efficiency actually saves some of the resource – an assumption that is valid in the examples given above. More fuel is left in the tank when fuel efficiency increases, less power needs to be generated to meet demand if transmission efficiency is improved, and so on. In the case of water, we cannot be sure what the implications for resource availability may be when efficiency is improved unless we trace fully where the "saved" water was previously going. Planners and politicians meanwhile are often encouraged to believe that the "saved" water will be available for allocation to new projects, new towns, and new industries.

In the debate about the "efficiency" term, the clearest and most positive critique (in the sense of providing an alternative) came from Willardson et al. (1994), and this provided the basis for the framework set out by the International Water Management Institute (Molden, 1997) and the terminology adopted by ICID (Perry, 2007) which was as follows.

Water use: Any deliberate application of water to a specified purpose. The term does not distinguish between uses that remove the water from further use (evaporation, transpiration, flows to saline sinks) and uses that have little quantitative impact on water availability (navigation, hydropower, most domestic uses).

All *Water use* goes to one of the following:

1. *Changes in storage* (positive or negative) – changes in storage include any flows to or from aquifers, in-system tanks, reservoirs, etc.
2. *Consumed fraction* (evaporation and transpiration) comprising:
   - 2.1. *Beneficial consumption*: Water evaporated or transpired for the intended purpose – for example evaporation from a cooling tower, transpiration from an irrigated crop.
   - 2.2. *Non-beneficial consumption*: Water evaporated or transpired for purposes other than the intended use – for example evaporation from water surfaces, riparian vegetation, waterlogged land.
3. Non-consumed fraction, comprising:
   - 3.1. *Recoverable fraction*: Water that can be captured and reused – for example, flows to drains that return to the river system and percolation from irrigated fields to aquifers; return flows from sewage systems.
   - 3.2. *Non-recoverable fraction*: Water that is lost to further use – for example, flows to saline groundwater sinks, deep aquifers that are not economically exploitable, or flows to the sea.

Identical terminology has been endorsed beyond ICID for example in the Journal of Hydro-Geology (Foster and Perry, 2010) and publications of the World Bank (Foster et al., 2009; Perry and Bucknall, 2009).

These terms are not perfect. Bart Snellen (personal communication) pointed out that the narrow definition of *water use* as water *deliberately* applied for some purpose seemed to exclude the contribution that rainfall makes, for example to beneficial consumption of rainfed crops as well as the total water supply to many irrigated crops grown in conditions of limited or erratic rainfall.

This suggests that at any scale, the accounting process should (as financial accounts do) be specified as a "sources and uses" table – with the study area having irrigation and/or rainfall and/or residual soil moisture as sources, while the uses include the consumed and non-consumed components as listed above.

As scale increases, the terminology remains valid. Changes in storage may increase to encompass aquifers and reservoirs rather than just soil moisture at field level. Some outflows are internalised at a larger scale as inflows to another part of the system – runoff

[1] A few years ago while visiting an irrigation improvement project in Yemen, I asked the field manager whether the water the project was saving would otherwise have recharged a local shallow aquifer. "Yes it did", he replied "that's why we call it 'calculated savings' – because it's only saved when you calculate it".

is inflow to a reservoir; percolation in one season becomes an irrigation source in the next. But the integrity of the analysis remains because the terminology embodies the hydrological consistency of continuity of mass. Similarly, other sectors should have no difficulty in presenting the current situation and impact of an intervention in the terms proposed here.

Nevertheless, the analysis and the labelling of the flows will generally require context-specific elaboration – particularly with respect to the disposition of the non-consumed fraction, which is entirely dependent on local factors, such as the quality and depth of any local aquifer and the potential to recapture runoff in other locations. Some interventions change water availability elsewhere in terms of time and quantity. An interesting study from South Africa (forthcoming) shows that upstream development of rainfed agriculture increases infiltration, reduces rainfall runoff and indeed reduces downstream flows during the wet season – but in the water-scarce dry season, the delayed releases from the extra infiltration to groundwater increase availability to downstream users. A (rare) win–win outcome, clearly identified by careful water accounting.

The disaggregation of water use into different sources highlights what can be managed, and what cannot. For example, evaporation from the soil during the long period of dormancy of winter wheat appears in the water accounts as a significant proportion of total consumption, but is not productive – but managing this flow is virtually impossible, just as heavy rain storms will generate runoff or percolation that cannot readily be avoided.

Finally, none of this begins to touch on water quality, which in some areas is the most important way in which freshwater supplies are rendered unfit for use (Norton et al., 2008). Using excessive water for irrigation may result in higher return flows and only marginal impacts on downstream availability; but water quality may be affected in the process, depending on whether the water passing through the soil strata deposits salt or picks up additional salt. Moreover, while irrigation can only consume the quantity of water applied, pollution can render multiples of the volume of water used in a process unfit for other uses.

Increasing numbers of papers are addressing the apparent paradox that "improved" irrigation leads to higher consumption and reduced availability elsewhere (in space, or in the case of aquifers, in time). These include Ward and Pulido-Velazquez (2008), IWMI (2006), Clemmens et al. (2008) and Burt (2010). In each of these interesting case studies, some version of "efficiency" is elaborated, then re-elaborated in terms that relate more clearly to hydrology and the law of conservation of mass. Agreeing and using the terms proposed above would short-cut that process and more clearly inform all readers of the analysis and conclusions drawn.

3. Applying water accounting to water productivity, and the observed non-linearity of yield/water relationships

Economists generally observe that successive incremental increases in an input to a production process result in progressively decreasing increments of output. Eventually, indeed, "too many cooks spoil the broth". The observation is so frequent that it has achieved the status of a law[2] – the law of diminishing returns.

Such relationships are widely observed in agriculture, and much of the research literature relates to optimising the rate of inputs such as fertilizer, pesticides, tillage, seeds and labour. "Optimising" in this context means applying an amount such that the extra value of production from the last increment of input equals the incremental cost of that input. At this point, in economic jargon, marginal revenue and marginal cost are equal, and beyond this point, incremental costs exceed incremental revenues so that profit is reduced. Given the uncertainty of many aspects of agriculture – pest attacks, storms, droughts, and varying prices, plus behavioural parameters such as risk aversion – precise optimisation is unlikely. Indeed it can be argued that the complexities underlying the production of a single crop are such as to preclude attribution of "productivity" to any input. Across climatic zones, soil types, and farming systems, this is true. But in controlled experiments in a specific location the question of whether water use (implying water from all sources, and going to each of the fractions defined in the proposed terminology) follows the law of diminishing returns has validity and is certainly of interest.

In support of this contention there are literally hundreds of papers reporting observations of the law of diminishing returns with respect to water, typically concluding that water use can be reduced while production is maintained, or that water use can be reduced significantly, with much smaller relative reductions in production – implying that significant savings in water can be achieved while maintaining production, or that production can be increased using the same amount of water.

Whichever way the observation is documented, the implication is that the productivity of water varies with the level of water use, in conformity with the law of diminishing returns. Some such claims do not stand up to careful scrutiny; some are soundly based on careful observations of field conditions; some can only fully be understood when the data are subjected to careful assessment of the water accounts.

The topic is extremely important because understanding how the productivity of water can be increased is a high priority where water resources are currently scarce and/or over-exploited. If productivity is maximised when yield per hectare is maximum, the target for water managers is rather simple and clear. If, on the other hand, there are significant potential gains to water productivity by reducing the water input (that is, the law of diminishing returns is applicable and significant) then managing water to achieve the optimum deficit is a high priority.

The terminology proposed above helps clarify the possible "sources" of observed diminishing returns to water. To investigate the mechanics underlying this, we start from the extreme where the calculated returns to water use are at their lowest. Consider a hypothetical irrigated field, where water management is poor, irrigation uniformity is low, and plentiful water from various sources is available.

3.1. Reducing the non-consumed fraction

If excessive irrigation causes water-logging in the root zone, yields are reduced, and will increase as water deliveries are reduced – an extreme but occasionally reported scenario, especially where drainage is poor.

Thereafter, the following sequence of improvements, in approximate ascending order of difficulty, also can be envisaged:

- Reduce irrigation deliveries so that runoff of irrigation water from the field is minimised.
- Reduce irrigation deliveries so that deep percolation of irrigation water is minimised.[3]

[2] We will get less and less extra output when we add additional doses of an input while holding other inputs fixed. In other words, the marginal product of each unit of input will decline as the amount of that input increases holding all other inputs constant Samuelson & Nordhaus, Microeconomics, 17th ed. page 110. McGraw Hill 2001.

[3] Note that salt issues are not addressed in this discussion; the minimum irrigation requirement may include a leaching fraction to maintain the salt balance in the rootzone.

- Improve irrigation scheduling so that runoff and deep percolation from rainfall are minimised.
- Level fields so that crops are irrigated uniformly.

These management interventions reduce water flows to the *non-consumed fraction*. Without knowing details of the local hydrological context, it is not possible to state whether these reductions in *water use* actually constitute savings that can be used elsewhere. For example, if excess deliveries during the rainy season, when water is plentiful, recharge an aquifer that is exploited in the dry season, then the "improved" management steps noted above will not result in real water savings – or at least not to full extent implied by the reduction in water use. In other cases, where aquifers are saline or runoff goes to the sea, such interventions indeed release water to alternative uses to the full extent indicated by the reduction in water delivered.

The observed impact of such interventions will be consistent with the perspective of diminishing returns to total water *use*, but until the water accounts are properly completed – identifying where the excess water was actually going – precise relationships between water and production are unclear.

3.2. Reducing the consumed fraction

3.2.1. Non-beneficial consumption

The next level of improvement addresses one element of the consumed fraction – water going to evaporation. Evaporation, where water is converted into vapour directly from energy reaching wet soil or foliage, does not contribute to crop transpiration and as such is non-beneficial consumption. It is a matter of debate whether the infrequent total wetting of the soil surface during conventional surface irrigation results in higher evaporative losses than frequent wetting of a small area during drip (Burt et al., 2002) irrigation, but the principles for the analysis are clear.

Some irrigation technologies – sprinkler systems in general, and especially rain guns – are prone to high evaporative losses (Bavi et al., 2009). Water evaporates directly into the air from the water jet, and also from the wetted leaves and soil. Not all writers have grasped the implications of this: a recent report in the UK,[4] explained (P78) how irrigation intensity in China could be significantly increased by adopting modern technologies such as sprinkler irrigation "to disperse water into the air so that it breaks down into small droplets". The conclusions reached in this report regarding China were, unsurprisingly, contrary to the conclusions of more careful analysts (e.g. Kendy et al., 2006).

Drip irrigation, by contrast, applies water directly to the base of the plant, with minimal exposure to the atmosphere and only a limited wetted area of soil. These technologies minimise non-beneficial evaporation of water, while adding complexity to the analysis. The evaporation from wet soil or foliage affects the microclimate around the crop, increasing humidity, decreasing potential transpiration of the crop, and thus reducing the rate of transpiration required to achieve a specific yield – a positive offset to the non-beneficial consumption. The extent of the feedback depends on the nature of the crop. In the case of an orchard crop or vineyard, where significant areas of soil are exposed to direct sunlight, the evaporation would have little impact on the transpiration potential. Where the crop densely covers the ground, losses from evaporation are much lower but impact more directly on crop transpiration.

In general, improvements such as these further reduce water use, and indeed in this case decrease water consumed, without necessarily affecting production – consistent with the law of diminishing returns to water.

3.3. Increasing the productivity of beneficial consumption

There is a strong relationship between crop transpiration and biomass formation. This is essentially because the stomata through which transpiration takes place are also the route of entry for carbon dioxide, which is the source of "material" for the plant to grow. If the stomata are only partially open because of lack of water, then a proportionate fall in carbon intake and biomass formation is observed.[5]

However, this relatively straightforward link between transpiration and biomass must be qualified in two important respects.

First, the proportion of biomass that is harvestable yield (for example, the mass of wheat grain as a proportion of total plant mass) is not constant, and is affected by the timing of any water stress. It is thus possible in theory to deliberately under-irrigate at insensitive periods, while fully irrigating at sensitive periods, and achieve a marginal increase is water productivity. The management level required to achieve this is high, and the risks (should an irrigation be missed accidentally when the crop is already stressed) are also high. Typically, the productivity increases (strictly defined as production per unit transpiration) that can be achieved for common field crops may be in the order of 10–15% (Perry et al., 2009).

Finally, there are three distinct and separate sources of reported curvature in the relationship between water consumed and production that are understood by specialists, but can be the source of considerable confusion in understanding the potential for improving water productivity.

3.3.1. Productivity in conditions of scarce and erratic rainfall

Rockström (2003) and Rost et al. (2009) have reported tremendous scope for increasing the productivity of rainfed agriculture, especially in sub-Saharan Africa, by shifting water consumption from evaporation to transpiration. At low yields per hectare, the productivity of water consumed is extremely low, while once a basic yield is achieved (2–3 t/ha) the productivity of water consumed is much higher.

What is being observed? One explanation that is consistent with farmer behaviour in many rainfed scenarios is that if rainfall is sparse and erratic, farmers plant at low seeding rates because this allows each plant the opportunity to draw from a relatively large "reservoir" of soil moisture from pre-season rain even though this results in high levels of evaporation from exposed soil. If seeding rates were higher, plants would compete with each other for moisture. In these conditions evaporation is high – especially early in the season when foliage is sparse. Where rainfall is more adequate, planting densities are higher and productivity (per hectare and per unit of water consumed) increase more than proportionately because higher plant density reduces evaporative losses.

Such an observation is consistent with experience elsewhere (Klein and Lyon, 2003), who reported that in a two-year, multiple site field study conducted in western Nebraska in 1999 and 2000, optimum dryland corn population varied from less than 7000 established plants per acre to more than 23,000 plants per acre, depending largely on available water resources.

[4] *A report of the economics of climate adaptation working group. Shaping climate-resilient development: a framework for decision-making*, 2009: ClimateWorks Foundation, Global Environment Facility, European Commission, McKinsey & Company, The Rockefeller Foundation, Standard Chartered Bank and Swiss Re.

[5] Some crops, especially fruits, are improved in quality (size, sugar content) by stressing at certain periods in the growing season. Here the objective is not productivity in the kg/m^3 sense, but rather productivity in the \$/m^3 sense. These are special cases, not relevant to this analysis.

The paradox of Rockstrom's "solution" is that it requires the controlled availability of the critical missing input, water. If farmers had that, they would probably not be operating at these extremely low levels of productivity in the first place.

3.3.2. Productivity and climate

It is noted earlier that the relationship between transpiration and biomass is linear. This statement requires a critically important qualification: linear *for given climatic conditions*.

Production is maximum when crop transpiration reaches its potential. But potential transpiration is a function of climate. Wheat grown in Australia potentially transpires almost three times as much water as wheat grown in the UK[6] because of the hotter, drier climate. If a graph of water productivity is plotted without standardising for climate, the result will be apparent curvature of the relationship between consumptive use (T or ET) and production. Such relationships, which have been published in important documents without clarification (e.g. IWMI's Comprehensive Assessment, quoting Zwart and Bastiaanssen), cannot be taken as evidence of a non-linear relationship between biomass and T, and does not constitute evidence of a law of diminishing returns between transpiration and biomass.

3.3.3. Productivity observed ex post

The final piece in this puzzle is perhaps the most complex, because it involves more than flow meters and lysimeters and complex crop models. It involves farmers.

The near linear relationship between transpiration and biomass formation that is reported in many papers (Howell, 1990, is particularly comprehensive) is based on conditions where nutrients are non-limiting. In other words, the crop has enough fertilizer and other nutrients to reach its potential yield for each given level of water availability. Under these conditions, scientists have repeatedly observed near linear relationships between T and biomass formation.

However, a farmer with some degree of uncertainty regarding water availability will typically "target" his inputs at some expected level of water availability. If the normal rainfall patterns allow 5 t/ha, there is little point in paying for fertilizer and other inputs consistent with 8 t/ha. The *ex post* observed relationship between T and yield will in consequence be non-linear because if rainfall exceeds expectations, yield will be constrained by nutrients (see Passioura, 2006 for field data that demonstrate this effect, and Nangia et al., 2008 for detailed modelling of the interactions between yield, water and nitrogen).

Here, curvature is a result of the divergence between ex ante expectation of water availability and what actually happened. Most importantly this is not an aspect of "diminishing returns" that can be exploited to achieve a better marginal return to the scarce resource – it is actually an observation of rational behaviour by farmers.

3.4. Conclusions regarding the relationship between crop water use and production

Economists like the law of diminishing returns, in part, because it allows them to optimise models with respect to inputs and outputs, prices, profits, and complex socio-economic objectives. Water is not a typical input for such analysis.

The most commonly reported ways in which water apparently exhibits decreasing marginal returns are not cases where we can confidently conclude that the reported reduction in use of water was a real "saving" in the way that, say, reduced fertilizer use is reflected in the availability of that fertilizer (or the money spent on it) for other purposes. For water, this will require careful, location specific analysis of where the saved water was going.

More sophisticated interventions may offer genuine improvements in the returns to water, but the management implications are generally quite demanding, and should be carefully evaluated in a hydrologically based accounting system. Only those farmers who are already close to the potential yield per hectare for their agro-climatic circumstances are likely to be able to exploit the intra-seasonal variations in relationships between yield and transpiration to achieve higher water productivity.

At the basic level of reported increases in productivity per unit of transpiration, there are several reasons to be at least cautious, indeed sceptical. Other factors – nutrient status, stochastic events, farmer education – can strongly influence observed relationships, while the underlying relationships, especially between water consumption and crop output, remain much closer to linearity than casual observation suggests.

Finally, none of this is to undervalue the potential for improved water management to achieve many desirable outcomes. Exactly what that potential is, however, must always be very carefully analysed in the local context, and within a proper accounting framework. This process will often reveal important additional insights into the processes being researched, and better expose planners and policymakers to the limitations to the options they face.

Table 1
Sample data on yield, water use efficiency and disposition of water.

	A	B	C
Yield (kg/ha)	**4581**	**4378**	**4031**
WUE (kg/m^3)	**0.58**	**0.72**	**0.64**
WATER (mm)	790	608	630
Transpiration (%)	**48**	**58**	**57**
Evaporation (%)	**26**	**22**	**22**
Percolation (%)	26	20	20
Transpiration (mm)	379	353	359
Evaporation (mm)	205	134	139
Percolation (mm)	205	122	126
WUE_T (kg/m^3)	1.21	1.24	1.12
WUE_{ET} (kg/m^3)	0.78	0.90	0.81

3.5. Case studies

Two papers submitted recently to Agricultural Water Management highlight some of the issues and potential for misinterpretation of water- and yield-related data. The papers are well researched, carefully analysed and clearly presented – indeed it is only because the authors present their data so clearly that re-interpretation is possible. The experimental designs and analysis appear to be of high quality. The comments below are thus not intended to be critical of the authors, but rather they emphasise the need for careful, precise and unambiguous water accounting.

3.5.1. Paper 1

The paper reports on aspects of three irrigation techniques – normal furrow irrigation; alternating furrow irrigation (i.e., irrigate half furrows in one cycle and the other half in the next cycle); and alternate furrow irrigation (i.e., irrigate every other furrow in each cycle).

For the purposes of this note, the techniques investigated are not of interest – only the fact that three different irrigation strategies (henceforth A, B, and C) were followed, and the outcomes were different. Prices and returns are also analysed in the paper, but are not of interest here.

The authors report in the abstract that:

[6] http://www.waterfootprint.org/?page=cal/WaterFootprintCalculator#result.

Table 2
Water use and productivity.

Treatment	Rain, mm	Irr, mm	D+R, mm	SWD, mm	Gross water use, mm	TOT CON, mm	Yield, t/ha	WUE_{ET}, kg/m^3	WUE_I, kg/m^3
11	595	604	130	4	1203	1073	28.4	2.6	4.7
12	595	418	11	43	1056	1045	26.9	2.6	6.4
13	595	317	11	61	973	962	24.2	2.5	7.6

Note: D+R is drainage and runoff; SWD is soil water depletion; gross water use is the sum of rainfall, irrigation, and soil water depletion.

Our results show that surface evaporation constitutes a large fraction of the irrigation water loss from the cropped field (more than 20%), and with the two [deficit] treatments nearly 40% of the evaporative water loss is saved. . .

The following information is reported for the three irrigation strategies:

- Yield (kg/ha)
- Water Use Efficiency (kg/m^3)
- Transpiration as a percentage of total irrigation water applied (there appears to have been no rainfall in any of the three years reported)
- Evaporation as a percentage of water applied

Table 1 assembles these data; figures in bold are data in the report; other numbers are derived by simple arithmetic from those data. Water applied is calculated from knowing Yield and Water Use Efficiency. Knowing the proportion of water going to Evaporation and Transpiration allows calculation of Percolation (runoff is reported as zero).

The first point to note is that while the authors report an increase in WUE between A and B of 24% (from line 2 – 0.72/0.58), this is in some measure due to a reduction in percolation. If the percolation is recoverable, then the increase in WUE between A and B falls to around 15%.

Second, the authors report that an increase in WUE as a result of “stomatal closure due to partial root drying” is demonstrated: in fact the variation in WUE_T is small, and indeed the lowest WUE_T is for one of the “deficit” irrigation strategies. It is only when WUE is computed on the basis of water *applied* that the supposed dramatic increase is observed.

In fact, this paper is better than many in that an attempt to separate E and T is made – recognising that E is non-beneficial consumption of water while T is the engine of production.

However, the “headline” conclusion in the abstract – “irrigation reduced by 30% with 4% fall in yield” – is seriously misleading. When the data are disaggregated we learn that:

- the improved technology reduces percolation (which may or may not be a “real” water saving);
- evaporation is substantially reduced, and the productivity of transpiration (WUE_T) which almost all authors report as constant, is here measured to vary by about $\pm$4%.

3.5.2. *Paper 2*

Another paper recently submitted to AWM, and still under processing, contains well-presented, correctly analysed data that also serve to highlight the potential to mis-report efficiencies and productivity. Table 2 uses data from a table in that paper, reporting rainfall, irrigation deliveries and crop yield.

Three irrigation treatments, delivering progressively smaller quantities of water, are reported.

Traditional calculations would report the irrigation efficiency as 78% ((604 − 130)/604) for treatment I1 and 96% ((317 − 11)/317) for treatment I3. The paper reports a dramatic improvement in the productivity of irrigation water (WUE_I) due to deficit irrigation from 4.7 kg/m^3 to 7.6 kg/m^3.

Closer examination of the details reveals a different picture.

Regarding irrigation efficiency, unless the final use of water going to D+R is known, the impact of deficit irrigation on other users cannot be assessed.

The reported increase in the productivity of irrigation water is a result of reductions in excess deliveries, a significant increase in the depletion of soil water, and an increase in effective rainfall.[7] Water productivity based on total water consumption[8] (WUE_{ET}) has actually declined marginally. The reported increase in WUE_I in fact results from attributing to the irrigation water the production achieved by transpiration of “extra” SWD and more rainfall.

The secondary impacts of these changes may be significant and are not addressed in the analysis as presented. SWD must be replaced either by additional rainfall or additional irrigation supplies. Increased utilisation of rainfall has likely implications for water availability downstream, which again may need to be restored through provision of more irrigation water.

4. Conclusions and recommendations

Understanding the options for dealing with water scarcity is a complex matter. Regarding the physical disposition of water, the terminology and analyses that are appropriate for designing individual projects of managing farm deliveries no longer give adequate information when there is competition for water at larger scales, and “losses” from one location are “sources” for another. In particular, the value-laden “efficiency” terms can mislead the uninformed reader.

This is not to deny the many benefits of better irrigation technology, but rather to recommend that impacts be set out in hydrologically consistent terminology, which requires careful evaluation of local water flows plus an evaluation of the final disposition of flows leaving the area.

Such analysis will also facilitate identification of those water flows that can be fully controlled by human intervention (for example, irrigation deliveries), those that can be influenced (for example, infiltration by land shaping or bare soil evaporation by mulching), and those that are beyond control (rainfall, evaporation from natural vegetation, open water and snow-covered fields).

The terminology adopted by ICID (Consumed fraction, comprising beneficial and non-beneficial consumption, and the Non-consumed fraction, comprising recoverable and non-recoverable flows) serves this purpose, particularly when combined with a fuller definition of water sources (rainfall, irrigation, soil moisture). While the terminology is particularly relevant to irrigation, it is equally helpful in analysing other water-using sectors.

This same terminology also facilitates the analysis of water productivity (Water Use Efficiency) which is critically important to food production and food security. Traditional approaches to measuring productivity have reported vast increases in “crop per drop” which on closer examination reveal that the central relationship

[7] As defined by an agriculturalist – the proportion of total rainfall consumed by the crop.

[8] Evaporation and transpiration are not measured separately in this study. The crop is a fodder with dense foliage, so that evaporation is likely to be a small proportion of ET.

(how much crop per unit of water *consumed*) has changed little if at all – and it is *consumption* of water that invariably affects availability elsewhere in the system.

Research reports, and the direction of research, would benefit from adoption of consistent terminology – which in addition is scale neutral and entirely "transferable" across the sectors that "use" water for consumptive and non-consumptive purposes.

The terminology and analytical approaches proposed here will come far short of providing a general understanding of how water should be managed. Every case will have its special considerations, such as pollution, the timing of water deliveries and timing and location of return flows. But all of these remaining difficulties can be ameliorated by this first step at establishing consistent, hydrologically sound reporting and analysis.

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