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EFFICIENT IRRIGATION; INEFFICIENT COMMUNICATION; FLAWED RECOMMENDATIONS†

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ABSTRACT

Concerns about scarcity of water have focused attention on irrigation, the largest water-using sector worldwide, which is widely seen as a low-value, wasteful and ''inefficient'' use for water. The terminology for this debate is, however, poorly defined – often failing even to distinguish between consumptive and non-consumptive uses. In consequence, technical interventions have not always led to the expected, desirable outcomes, and the recommendations in many reports and papers are at best dubious, at worst simply wrong. The history of the analysis of ''irrigation efficiency'' is traced, and compared with the science of hydrology, which offers consistent terminology for various scales of analysis from field through irrigation scheme to region and basin. Based on the work of various previous writers, an analytical framework and associated terms are proposed to better serve the needs of technical specialists from all water-using sectors, policymakers and planners in achieving more productive use of water and tracing the implications of interventions on other uses and users. ICID recommends that this terminology be used in the analysis of water resources management at all scales, and form the basis for its research papers and other published outputs. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS: irrigation efficiency; water management; losses; fractions

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RÉSUMÉ

Les préoccupations relatives à la raréfaction de l'eau ont concentré l'attention sur l'irrigation, le secteur le plus consommateur d'eau dans le monde, qui est couramment considéré comme un usage de faible valeur ajoutée, gaspilleur et inefficace. Les termes de ce débat sont cependant mal définis – ils ne permettent même pas, le plus souvent, de distinguer entre usages impliquant une consommation et usages ne l'impliquant pas. En conséquence, les interventions techniques n'ont pas toujours donné les résultats souhaitables attendus, et les recommandations de nombre de rapports et revues sont au mieux douteuses, au pire, tout simplement mauvaises. L'histoire de l'analyse de l' « efficacité de l'irrigation » est présentée, et comparée à la science de l'hydrologie qui propose une terminologie confirmée pour différentes échelles d'analyse allant de la parcelle jusqu'à la région et au bassin versant, en passant par le périmètre d'irrigation. A partir du travail de divers auteurs, sont proposés un cadre analytique et le vocabulaire correspondant afin de mieux répondre aux besoins des spécialistes techniques dans tous les usages de l'eau, d'aider les décideurs et les planificateurs dans leurs efforts pour atteindre une utilisation plus productive de l'eau, et de repérer les impacts des interventions sur d'autres usages et d'autres usagers. La CIID recommande que cette terminologie soit employée dans l'analyse de la gestion des ressources en eau à tous les

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niveaux, et constitue une base de référence pour les travaux de recherche et autres publications.

MOTS CLÉS: éfficacité de l'irrigation; gestion de l'eau; pertes; fractions

Be careful what you wish for: it may come true.
Adage

INTRODUCTION

Irrigation is widely accused of being a wasteful, low-value use of water. The debate about the contribution that irrigation makes, and the potential benefits that could be achieved by reducing waste and transferring water to higher-value uses is not helped by the widespread confusion in the literature about what constitutes ''water use''. Rarely are clear distinctions made between diversion and consumption of water. Although in the typical house connected to a main sewer system, some 95% of the water delivered by the water utility is collected and returned for treatment and subsequent reuse within the water resources system, wild claims are made in respected journals (*Scientific American*, February 2001) that vast quantities of water can be ''saved'' by increasing ''efficiency'' through use of low-flow showers and mini-flush toilets. In fact the consumptive use of a shower, like a bath or a toilet, is nearly zero if it is connected to a sewer. It is the hydrological location of the diversion and return flows that determines the impact of shower design on total water use and consumption.

This issue was highlighted in a recent exchange on the Winrock Water website. Peter Gleick submitted two notes (Gleick, 2006a, b) as a basis for explaining how the introduction of low-flow toilets saved water. The first note – a memorandum – summarises the results of an analysis of the impact of introducing low-flow toilets on ''urban demand'' for water. The analysis demonstrates substantial reductions in something called ''real demand'' for water, and accuses the California Department of Water Resources of failing properly to account for this potential. The associated document is a hydrologic flow chart showing diversions to two cities for various uses, return flows to the river system, and the final outflow to the ocean. Surprisingly, the difference in final outflow between the original case and the case after improved, efficient, ''real demand''-reducing toilets are installed is zero – so a downstream user, hoping to find more water available following introduction of ''efficient'' toilets would be disappointed. In fact the analysis could have made the very important point that if the return flows from the toilets were *not* recovered for downstream use, then the ''savings'' would indeed have been observable as increased downstream availability: hydrological context is all important, and masked by the terminology. Gleick claims quite rightly that low-flow toilets reduce water diversions by cities and thus reduce costs for water treatment, reduce the need for upstream water storage to sustain supplies during droughts, and reduce local dewatering of streams between points of diversion and points of return. However, claims implying the most obvious ''saving'' – of physical, wet, useful water – are misleading, indeed wrong.

Such confusion can be observed in authoritative data sets. The Pacific Institute (reference: http://worldwater.org/data.html, accessed 1 May 2007) quotes Egypt's annual renewable water resource as 86.8 km^3—a surprisingly high figure, given that Egypt's agreed share of the Nile is 55.5 billion m^3, and rainfall is negligible. Meanwhile, Earthtrends (reference: http://earthtrends.wri.org/searchable_db/, accessed 1 May 2007) reports a figure of 58 km^3, with ''Internal renewable resources adding an additional 1 cubic kilometer''. Both sources refer to the FAO's AQUASTAT as a source of information. That estimates of the available water in the most regulated and documented large water system in the world should vary by some 50% must be a cause for concern.

The analysis of irrigation is also prone to unexpected outcomes. In irrigation, the very purpose of the use is to consume the water – removing it, through evaporation and transpiration from the hydrological cycle – and an increase in efficiency frequently means that consumption by crops is increased because the service more precisely and uniformly matches the water needs of the crop (this in turn tends to increase the value of the water, and hence

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demand also increases: thus higher efficiency can be expected to cause higher consumption and higher demand). This is not to say that low efficiency is good, but rather that ''efficiency'', unrelated to context, is worse than meaningless, and can cause wrong decisions to be made economically, hydrologically and ecologically.

Getting the terminology right, so that irrigation engineers, water supply and sanitation engineers, hydrologists, planners, and journals can all contribute meaningfully to an important debate is a high priority, and this paper aims to initiate a debate in the ICID community that will bring about clarity and consistency.

Others are already working in this direction. The draft water requirements chapter of the upcoming revision of the American Society of Agricultural Engineers (ASAE) Monograph on Design and Operation of Irrigation Systems, and the upcoming revision of the American Society of Civil Engineers (ASCE) Manual 70 (Evapotranspiration and Irrigation Water Requirements), are expected to replace ''efficiency'' terms with alternative terminology that reduces the scope for confusion and misuse.

BACKGROUND

Food production and food security are intrinsically linked to water availability and water security – and for most countries in the developing world, water security means irrigation – 40% of foodgrain is produced on the 20% of arable land that is irrigated. Worldwide, some 270 million ha are irrigated, accounting for two-thirds of total water consumption, which is currently estimated at 4 billion $m^3\ yr^{-1}$. In developing countries the proportion of water going to irrigation is often much higher, at 75–85% of total use.

Until quite recently, most river flows were still adequate to meet demand throughout the typical year, so that irrigation development could largely be seen and analysed separately from other water uses, and separately from the more general study of hydrology. Now, in many basins, water use is approaching full development: demands from increasingly wealthy urban consumers are increasing sharply, and concerns to protect, preserve, and in some cases restore environmental flows are receiving attention from all parts of society. Once there is competition, all uses – and particularly irrigation, the prime user of water – must be analysed in its broader hydrological context, and the basis for that analysis must be a framework that properly provides for comparison and assessment of the various types of water use.

THE ROLE OF WATER ACCOUNTING

The most common use of the term ''accounting'' refers to financial record keeping. The principles on which financial accounting is based are common to any type of accounts: financial accounting is the application of a set of definitions and rules to incomes, expenditures, and other transactions so as to describe, for a given period of time, the financial flows, including increases and decreases in savings, profits and losses for a financial entity.

We are accustomed to many of the terms used in financial accounting – expenditure, income, surplus, deficit – and can readily understand many associated concepts such as profit and loss. We are also accustomed to understanding that the procedures are independent of scale – each term has the same meaning whether applied to a corner shop or a multinational corporation. Furthermore, the temporal frame of reference must be appropriate: sales in one season may be much higher or lower than sales in another, so that accounts must either be qualified as unrepresentative of a whole year, or must include the whole year.

Historically, the science of hydrology and the practice of irrigation engineering have developed at different scales. Different objectives have determined the basis for accounting and, in consequence, there is no common set of definitions on which a compatible accounting system can be based. When irrigation becomes a significant component of basin hydrology, the divergence of terminology poses at least a difficulty, and sometimes a threat to the understanding of irrigation and other categories of water use within the overall hydrological context.

At the global scale and in the long term, evaporation from water bodies plus evapo-transpiration from land and vegetation must equal precipitation – but as soon as the frame of reference is less than the global, long-term scale, careful attention must be paid to the flows across the borders of the selected spatial and temporal reference frame. As the frame of reference gets smaller (spatially, from river basins, to land use classes, local areas, irrigation schemes and fields, and temporally from multi-year to year, season, crop period, an irrigation cycle) ''cross border'' flows becomes increasingly complex and significant.

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THE HYDROLOGICAL APPROACH TO ACCOUNTING

The equation of mass continuity provides that the sum of inputs equals the sum of outputs plus the sum of changes in storage so that at the global scale:

$$P = R + E + T + dS$$

where P is precipitation, R is runoff, E and T are evaporation and transpiration and dS is the sum of the changes in water storages (e.g. glaciers, snowpack, lakes, rivers, soil moisture and groundwater).

At lesser scales of observation, human interventions can generate additional local inflows through trans-basin diversions of surface or groundwater, and also substantially change the ‘‘natural’’ levels of E and T – by changing land use so as to ‘‘conserve’’ water for *in situ* use by crops (locally reducing R), or developing drainage to remove excess water (so reducing E and increasing R). At any scale from basin to field, the resulting mass balance will be

$$P + I = R + E + T + O + dS$$

where I and O are other inflows and outflows. In the case of a river basin I and O might be inter-basin transfers of surface or groundwater – and the boundaries of the groundwater aquifer may not coincide with the boundaries of the surface runoff system. In the case of a country, they would be transboundary inflows from upstream countries and flows to downstream countries, or other committed outflows such as may be required to preserve the environmental and ecological status of the river system.

Unfortunately, of course, these components of the balance vary considerably from year to year. Analysing the data over a number of years will provide more reliable statistical estimates of mean flows and variability, and of course natural and man-made storages provide the capacity to reduce variability.

A key, desirable feature of the hydrological approach to accounting is the uniformity of terms and meanings to the various parameters – at any spatial or temporal scale.

THE IRRIGATION APPROACH TO ACCOUNTING

In engineering, dimensionless ratios of inputs to desired outputs are routinely assigned the title of ‘‘efficiencies’’: the transmission efficiency of the electrical grid is the ratio of the energy received by consumers to the energy delivered into the grid from the generation stations; the thermodynamic efficiency of a central heating boiler is the heat energy absorbed by the water in the boiler divided by the heat energy in the fuel heating the boiler; the mechanical efficiency of any device – a bicycle, for example – is the ratio of the energy transferred through the wheels to the road to the energy applied to the pedals. All these efficiency concepts have in common that:

- high efficiency reflects low losses;
- losses are a non-recoverable waste of resources;
- reductions in ‘‘losses’’ will mean that more of the input is available for alternative uses;
- and, by implication high efficiency is ‘‘good’’.

Engineering considerations have historically dominated the approach to water accounting in the irrigation sector.[2] Facilities (diversion weirs, dams, canals, pumps, etc.) are sized according to the available or required water – and the proposed area for irrigation is sized to match the expected *supply* of water at the field to the *demand* for water of the expected crops under the local climatic conditions.

Economy of design implied that expensive facilities should be of the minimum necessary size, and that as much as possible of the water that the facilities had stored, diverted or pumped should reach its intended productive purpose of growing more crops. Much attention in consequence was paid to the ratios between the volume of water available at the diversion point or storage reservoir; the volume of water actually delivered to the crop, and the volume of water utilised by the crop.

The concept of efficiency in irrigation evolved some 60 years ago. Following extensive field work in the 1940s, measuring the quantities of water applied to fields compared to the actual evapotranspiration requirement, Israelsen (1950) stated: ‘‘With a given quantity of water diverted from a river, the larger the proportion that is stored in the

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root-zone soil of the irrigated farms and held there until absorbed by plants and transpired by them, the larger will be the total crop yield.'' He then defined *irrigation efficiency* as the ratio of the irrigation water consumed by the crops of an irrigation farm or scheme to the water diverted from a river or other natural water source into the farm or scheme canal or canals. In equation form, he defined *irrigation efficiency* as

$$E_i = W_c / W_r$$

where W_c is irrigation water consumed by the crops and W_r is the water diverted from a river or other natural source (Israelsen, 1950, Equation 1). Essentially, he defined irrigation efficiency as the ratio of water consumed by the intended purpose to that diverted.

This basic approach to irrigation accounting remained fundamentally unchanged for over 40 years. Refinements were suggested – for example, Hansen (1960) pointed out that if the water applied is less than the potential consumption by the crop, the water-application efficiency may approach 100%, but the irrigation practice may be poor and the crop yield low – so that high efficiency was not reliably correlated to good performance. He proposed to disaggregate efficiency into a number of components, and proposed an overall concept of consumptive use efficiency.

Jensen (1967) pointed out that for sustained irrigated agriculture, the quantity of water effectively used to control soil salinity (the leaching fraction) should be considered as beneficial use. Therefore, he defined irrigation efficiency as the ratio of ET of irrigation water plus the water ''necessary'' for leaching on a steady-state basis to the volume of water diverted, stored, or pumped specifically for irrigation. Subsequently, Jensen (2002) has pointed out that this resulted in the numerator containing a consumptive component and a small non-consumptive component, making water balance calculations more complex.

Bos and Nugteren (1974, 1982) published the results of a joint effort of the International Commission on Irrigation and Drainage (ICID), the University of Agriculture, Wageningen, and the International Institute for Land Reclamation and Improvement (ILRI), Wageningen. The definitions of efficiency terms were refined in the 1982 edition. Distribution efficiency was defined as the ratio of the volume of water furnished to the fields to the volume of water delivered to the distribution system. Field application efficiency was defined as the ratio of the volume of irrigation water needed, and made available, for ET by the crop to avoid undesirable water stress in the plants throughout the growing cycle to the volume of water furnished to the fields. Combining these various figures at appropriate scales provided measures of efficiency at field, farm, tertiary, scheme and district level.

Despite these variations and enhancements, Israelsen's original definition of efficiency, relating the water used by the crop to the water diverted at some point remained the underlying accounting basis in irrigation. Since the various losses (in distribution and field application) were essential knowledge to those designing the irrigation systems, this accounting basis was appropriate and relevant to that engineering purpose. High efficiency implied that a high proportion of the water available at the head of a scheme was being used for the design purpose of augmenting crop transpiration – an appropriate engineering objective.

However, in 1979, a US Interagency Task Force completed a report, *Irrigation Water Use and Management* (Interagency TF, 1979). The Task Force based its report on available literature and input from a number of specialists, and undertook a detailed review of field data on irrigation efficiency and related information on water laws and institutions, causes of inefficiencies and their results. Regarding irrigation efficiency, they stated:

> ''[A]ny report dealing with irrigation efficiencies must first define ''efficiency'' with a great deal of care. Many different and sometimes conflicting definitions have been published. It is frequently assumed that because irrigation efficiency is low, much irrigation water is wasted. This is not necessarily so.'' (p. 22).

This significant change in thinking was endorsed by Jensen (1993) who suggested changing the name of the ''efficiency'' ratio to a term such as a *consumptive use coefficient*, C_{cu}, to represent the fraction of water diverted, or applied to a field, farm, or scheme that is consumed. The fraction that is not consumed would be $C_{ncu} = (1 - C_{cu})$. In making this recommendation, Jensen referred to water balance and river basin studies, providing an important intellectual link, as the 1979 Task Force had done, to the holistic approach of the hydrologist.

The next 10 years saw a number of important contributions to the ''irrigation efficiency'' debate: Willardson *et al*. (1994), Allen *et al*. (1996, 1997), and Willardson and Allen (1998) suggested that the ''classical'' efficiency term was outmoded. This series of papers recommended using ratios or fractions to define water use so as to better

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consider impacts of return flows, and almost equally importantly to move away from the value-laden term ‘‘efficiency’’.

The general thrust of these papers was to divide water diverted to irrigation schemes into the following components:

- The *consumed* fraction (essentially ET), comprising:
  - *beneficial* consumption (for the purpose intended or other beneficial use such as environmental purposes);
  - *non-beneficial* consumption such as weeds or resulting from capillary rise during a fallow period);
- The *non-consumed* fraction, comprising:
  - *recoverable* flows (water flowing to drains and back into the river system for possible diversion downstream, and percolation to freshwater aquifers);
  - *non-recoverable* flows (percolations to saline aquifers, outflow to drains that have no downstream diversions or direct outflow to the ocean).

This set of ideas adds importantly to Israelsen’s original concept: first it focuses attention on what is really a loss (non-beneficial ET, and the non-recoverable component of the non-consumed fraction). This in turn points to more careful consideration of the recoverable, non-consumed fraction: in many monsoon climates, the non-consumed but recoverable fraction that contributes to groundwater recharge in the rainy season is the basis for productive groundwater irrigation in the dry season. Improving classical irrigation efficiency during the monsoon would have a negative impact on dry-season availability, at least on a regional basis. Similarly, where investments are proposed to improve classical irrigation efficiency, it is essential to know whether the ‘‘losses’’ that are being reduced are in fact lost at all.[3]

Non-engineers have added to the literature on the subject of irrigation efficiency. That of Seckler (1993) provided the foundation used in the development of the new International Water Management Institute (IWMI) paradigm referred to as the ‘‘IWMI Paradigm’’ which analyses irrigation water use in the context of the water balance of the river basin (Perry, 1999) – while at the outset stating that the ideas were not novel:

Others have documented similar views in the past – indeed all hydrological models incorporate much of this logic as a matter of course.

Molden (1997) developed procedures for accounting for water use, or water accounting based on a water balance approach. Water accounting is a procedure for analysing the uses, depletion, and productivity of water in a water basin context. A key term is *water depletion*, which is the use or removal of water from a water basin such that it is permanently unavailable for further use. He described process and non-process depletions. *Process depletion* is where water is depleted to produce an intended good. In agriculture, process depletion is transpiration plus that incorporated into plant tissues – the product. *Non-process depletion* includes evaporation from soil and water surfaces and any non-evaporated component that does not return to the freshwater resource. The *depleted fraction* is that part of inflow that is depleted by both process and non-process uses of water. While the term ‘‘depletion’’ allows the amalgamation of all the components that remove water from the renewable water resource system (evaporation, transpiration, flows to sinks and pollution), it does not conform to the more general meaning of the term, which implies removal from storage (e.g. depletion of an aquifer or reservoir).

Molden further suggests that the productivity of water can be measured against gross or net inflow, depleted water, process-depleted water, or available water in contrast to the production per unit of water consumed in ET (Viets, 1962). Water accounting can be done at various levels such as the field, irrigation service, basin or sub-basin levels. Molden and Sakthivadivel (1999) presented a detailed example of water accounting at the basin level using data from Egypt’s Nile River where detailed information on water use and productivity was available. This study made clear how the computed ‘‘classical’’ efficiency of irrigation varied substantially with scale: measured at the basin level, Egyptian irrigation is approximately twice as efficient as it is at field scale. Molden and Sakthivadivel (1999) presented another example for a district in Sri Lanka.

A paradox in the terminology advocated by IWMI in these and other papers is introduction of the term ‘‘basin efficiency’’ to indicate the extent to which the natural runoff of the basin is diverted to consumptive uses. Given the contribution that IWMI made, both in supporting the proposals of others to use less confusing terms and in its own proposals, as summarised above, it is surprising that the ‘‘efficiency’’ word should reappear. Just as Hansen (1960)

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pointed out that a high efficiency based on Israelsen's original concept was no sure indicator of good irrigation performance, so a high ''basin efficiency'' is no indicator of good development (indeed in some basins – for example in Libya, Saudi Arabia, Yemen, southern Morocco and Jordan – the ''efficiency'' frequently exceeds 100% due to overexploitation of aquifers. Most observers would agree that decreasing ''basin efficiency'' in such contexts would be an improvement).

The proportion of the available water that is consumed is an important indicator of development of a basin, but the *desirable* level of such consumption depends on the season, the precipitation, and the quantity of water that is needed to support natural consumptive and non-consumptive uses that depend upon streamflow and groundwater recharge. In other words, the answer to the question ''what is the optimum basin efficiency?'' is ''it depends on the local and regional situations'' – which is hardly an addition to knowledge.

However, the idea that there are useful indicators beyond the facts of the hydrological flows continues to flourish. In an important contribution to the concept that water quality and quantity are both important, Keller and Keller (1995) proposed the concept of *effective irrigation efficiency*. In their analysis, where the quality of drainage water is too poor for direct reuse, the quantity of water required to dilute the effluent to a usable quality is counted as consumed water. For the specific purpose of irrigation, where the pollution is salt and the definition of acceptable quality can be specified, this methodology has clear merits – but its weakness lies in the fact that the computed effective efficiency varies depending upon (a) the nature of the pollutant, and (b) the nature of the downstream use. While useful as a demonstration of the relationship between quality and quality, indicators of performance should preferably depend on internal factors within the control of the designer/operator. This suggests that analysis of pollution issues will always have to be a distinct and separate activity from the hydrological analysis of water flows.

Solomon and Burt (1999) have proposed the concept of ''irrigation sagacity'' as an indicator of management quality; the European Water Framework Directive – as interpreted by the UK's Environment Agency – emphasised efficient water use, followed by recognition that a public consultation on what ''efficiency'' means would be required;[4] Knox (2006) in an attempt to assist UK farmers through this mire has proposed a system to ''audit'' performance of irrigation systems and identify potential areas for ''improvement'' – largely aimed at improving the traditional interpretation of efficiency.

Perry (1999) quotes other examples of perverse outcomes – anonymised, because the purpose is example, not criticism:

1. *Tradable water rights and downstream users*: In a South American country, tradable water rights were introduced, with rights based on historical entitlements to divert water. Upstream users invested in high ''efficiency'' on-farm technology, and were able to maintain the consumption of water by their crops while decreasing the associated diversion. The water saved by this increase in ''efficiency'' was sold to nearby towns and cities, and downstream users who had depended on the return flows from previous ''losses'' were left with substantially reduced water supplies;
2. *Investment to ''save'' water to other uses*: In the USA, a city offered to pay for lining of irrigation canals in a nearby irrigation district, with the water thus saved to be made available to the city for domestic and industrial use. Presumed ''efficiency'' of the irrigation scheme, which was mainly gravity irrigation through unlined canals, was capable of substantial improvement. Detailed analysis of the situation, as a basis for defining the ''savings'' attributable to the investment and hence the water available for transfer, showed that at the basin level, some 80–90% of water was already consumed and potential ''savings'' were thus minimal;
3. *Water consumption and improved delivery technology*: In a water-short country in the Middle East, on-farm investments were made to increase measured ''efficiency'' from 40–50% to 60–70%, releasing water for further expansion of the irrigated area. Measurements to date show that the improved technology results in increased crop yields and increased water consumption – a direct confirmation of the many existing studies showing the positive relationship between yield and evapotranspiration, but not the hoped-for saving in water!
4. *Improved agricultural practices save water*: A research institute developed a new technology for growing rice – wet seeding – which significantly reduces the volume of water applied to the field. However, a larger area is kept fully wetted for a longer period than with the traditional nursery system (where only a few per cent of the final cropped area must be kept fully wetted for the first 30–40 days). It is not clear yet whether the water consumed through ET is increased, reduced, or unaffected by the new technology;

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5. *Technology improvements and multiple use of water*: Sometimes ‘‘perverse’’ outcomes of increased efficiencies are legally constrained to control hydrologic impacts. In a European country, ‘‘inefficient’’ surface irrigation has been reintroduced in some areas because shifts to sprinkler and drip irrigation resulted in severe depletion of aquifers on which urban supplies were dependent. In a recent US Supreme Court decision,[5] an ‘‘upstream’’ state agreed to constrain farmers along mountain streams from improving irrigation efficiencies and thereby increasing the consumed component of their bulk diversions.

THREE ASIDES: WATER HARVESTING, COLOURED WATER AND WATER USE EFFICIENCY

While these three asides, water harvesting, coloured water and water use efficiency, do not relate directly to the issue of irrigation efficiency and related terminology, they are certainly contributing factors to many misunderstandings about hydrology and the impact of human activities on water availability.

Water harvesting

Irrigation is the artificial capture and application of water to support crops, usually understood to involve dams, inundation canals or wells, but in fact there is a continuum of intervention from land preparation to induce infiltration of rain, through mulching, contour bunding and other forms of catchment management to small farm tanks that approach irrigation in the conventional sense.

Water harvesting is a common name for the simpler of these interventions. This word ‘‘harvest’’ implies that any water that is not captured for local use is a ‘‘loss’’, while in fact it might be the runoff serving a stream or infiltration to an aquifer. Excessive water harvesting will dry up rivers, wetlands and estuaries just as effectively as large dams.

Coloured water

In a technical background document for the 1996 World Food Summit in Rome (FAO, 1996) reference is made to a proposed colour scheme designed to ‘‘explain’’ water availability:

> The fraction of water evaporated is sometimes called green water, that is, the water supply for all non-irrigated vegetation, including forests and woodlands, grasslands and rain-fed crops. After discounting evaporation from continental rainfall, there remains an annual 40,000 billion m^3 of fresh water in lakes, reservoirs, streams and aquifers in active exchange with surface water. This so-called blue water is unevenly distributed over space and time and is a transient presence while it flows to join a water sink such as the sea or a saltpan.

These specifications are not entirely clear; the IWMI website[6] elaborates as follows:

> Sixty percent of all rainfall never reaches a river or aquifer; it replenishes the soil moisture and evaporates from the soil or is transpired by plants – we call this the green water.

This definition (which in hydrological terms seems to correspond to that proportion of total ET that is not the result of irrigation) rather implies that ‘‘green’’ water is unmanageable, but IWMI goes on to say that:

> Green water cannot be piped or drunk, and is therefore safely ignored by urban water managers. But green water is crucial to plants, both in ecosystems and in agriculture, and *needs to be managed carefully* (emphasis added).

IWMI then go further to suggest that:

> The traditional split between rainfed and irrigated agriculture has become obsolete. It should be replaced by water management for agriculture, accounting for the complete spectrum from pure rainfed, via rainwater harvesting, to supplemental or deficit, to full irrigation.

This final statement seems rather to confirm that the distinction made between blue and green water is itself artificial and unhelpful.

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A possible purpose of these new terms is to provide simplified information to non-specialist users. In fact, their adoption by agencies such as FAO only adds confusion to an area where well- proven terminology has been settled for years: the hydrologic cycle contains no components with names such as green water, blue water, grey water or any other colours – such terms being better left to poets or politicians. And hydrological analysis distinguishes carefully between stocks and flows: the above listing mixes streams, which are water flows – and generally account for the referenced 40 000 billion m^3 of available fresh water – with reservoirs, lakes and aquifers – which are stocks of water – indeed the *stock* in the Great Lakes of Canada alone equals half the world's annual river *flows*. The colour of the water in Canada's lakes is as yet unspecified.

The analytical basis underlying the proposed colour scheme is seriously flawed: the definition of "green" water fails to distinguish between water that is transpired through rainfed agriculture or through natural vegetation; water that evaporates directly, and not through a plant; and water that forms part of the supply to crops that also receive irrigation.[7]

Furthermore, the framework is incomplete – inter-temporal storage as groundwater is not assigned a colour, so presumably goes unrecognised. Worse, the colour-coding separation gives the impression that there are various independent sources of water – so some users can exploit green water while others exploit blue water: in fact once any management or use affects the natural hydrology then all colours are affected.

Colour coding obscures rather than illuminates the hydrological realities of interventions into water systems, leading politicians and policymakers to believe that there are independent "sources" of water that contribute independently to solving their shortages.

Most specialists in this area are fully capable of understanding the results of proper hydrological analysis.

Water use efficiency (WUE)

This topic does not relate to the hydrological problems with engineering definitions of efficiency; rather the term itself is confusing and is used in confused ways. In the context of irrigation, WUE is generally defined as the crop yield per unit of water[8] – in fact it is what an economist would call the productivity of water. However, the term is frequently simply interchanged with irrigation efficiency, or is misquoted as, for example, "efficiency of irrigation water use" – which appears in the title of perhaps the most thorough overview of the topic of irrigation efficiency (Wolters, 1992) in which WUE is not even mentioned. A survey of recent issues of *Irrigation and Drainage* reveals the following examples: Khan *et al*. (2003) use WUE in its strict (irrigation) sense, with units kg m^{-1} (albeit units which violate the engineering requirement that an efficiency be a dimensionless ratio); Hamdy *et al*. (2003) include "water productivity" in the title of their paper, yet refer to "water use efficiency" in the abstract and use the term "water productivity" in the key words. Sarwar and Perry (2002) use only the term "water productivity". Finally, Rajput and Patel (2005) refer to *field* water use efficiency, but use the term both in respect of saving "losses" and increasing productivity – without distinction as to which is WUE and which is irrigation efficiency in the classical sense.

These examples, and many others, confirm that the meaning of water use efficiency is not well agreed or applied in the context of irrigation. Elsewhere, in the context of plant biology, the term is also widely used, though apparently with many of the difficulties that we face in respect of definitions of irrigation terms:

> The term water use efficiency (WUE) is rather an unfortunate misnomer. Firstly, the water taken up by a plant canopy and transpired or lost in evaporation is only "used" in the very broadest sense – in reality only a very small part of the water taken up is actually utilised in the construction of carbohydrates or even in the composition of plant tissue. Furthermore, as usually defined, it is not even a true "efficiency", which is a term conventionally reserved for the dimensionless ratio between the output of a quantity and its input (Jones, 2004).

CONCLUSIONS AND RECOMMENDATIONS

Hydrology began as the study of a natural process: the streamflow in rivers resulting from precipitation on naturally vegetated catchments. While water remained plentiful, impacts of human intervention on these natural processes

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were generally small and rarely interfered with each other. To ensure that investments were sound, the traditional attention to classical efficiency in engineering terms was appropriate and useful.

Progressively, human intervention has modified the natural process through changes to land use and the development of storage and diversion works that (by now) substantially modify natural streamflows.

As shown in this paper, the current nomenclature related to how irrigation interacts with hydrology – particularly terms such as efficiency and loss – and produces confusing results for planners and policymakers involved in addressing issues of water scarcity. Even irrigation professionals use various terms interchangeably and without due regard to the clarity of their recommendations.

The first priority is to define terms that can be used unambiguously by planners, hydrologists, engineers and others, such as lawyers and economists, concerned with analysing water resources. Given that the science of hydrology has been in place for many years, it provides the most tested framework, and whatever the irrigation profession finally opts for should be entirely consistent with hydrological analysis.

Beyond the general framework, each speciality will have its own additional set of parameters of interest, but terminology for the basic parameters should be common. It is desirable that the parameters used should not be value-laden, and it is essential that they should be location- and scale-independent – parameter definitions at the irrigation scheme level should not be invalidated by either the location of the scheme, or when we look at the basin rather than a specific scheme.

After in-depth consultations and wide circulation of the draft paper the following terms are recommended:

1. *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 sinks) and uses that have little quantitative impact on water availability (navigation, hydropower, most domestic uses).
2. *Withdrawal*: water abstracted from streams, groundwater or storage for any *use* **–** irrigation, domestic water supply, etc.
3. Within withdrawals, following the recommendations of Willardson *et al*. (1994) and Allen *et al*. (1997), water would go to:

a. *Changes in storage* (positive or negative) – changes in storage include any flows to or from aquifers, in-system tanks, reservoirs, etc. The key characteristic of storage is that the water entering and leaving is essentially of the same quality.

b. *Consumed fraction* (evaporation and transpiration) comprising:

i. *Beneficial consumption*: Water evaporated or transpired for the intended purpose – for example evaporation from a cooling tower, transpiration from an irrigated crop.

ii. *Non-beneficial consumption*: Water evaporated or transpired for purposes other than the intended[9] use – for example evaporation from water surfaces, riparian vegetation, waterlogged land.

c. *Non-consumed fraction*, comprising:

i. *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.

ii. *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.

This framework is consistent with hydrology – it meets the criterion of continuity of mass. It recognizes that water is water – it is not somehow differentiated by colour or source.

Within this framework it would be clear that the key areas of attention when water is scarce would be to reduce non-beneficial consumption, and to reduce non-recoverable flows *to the extent that proper hydrological analysis shows that no unintended consequences of such reductions occur*. It would also be clear that whether a flow was recoverable or not would be location-specific – so that the recommendations for irrigation technology would (for example) depend on groundwater conditions, and proximity to the sea.

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This desirable step forward in clarity should not be interpreted as a simplification in measurement: separation of crop transpiration (clearly beneficial consumption) from the evaporation from wet soil in the field where the crop grows (a non-beneficial consumption) is not simple – and in fact some of the evaporation has the effect of reducing the transpiration demand of the crop, so has a beneficial component; water flowing to a saline aquifer is deemed to be a non-recoverable non-consumed fraction, but the precise borderline between the quality of water that meets the ''recoverable'' criterion is not absolute. The benefit of the proposed analytical framework is that such issues will be overtly and transparently identified in the analysis, and that attention is focused on those components of the water balance which most importantly influence the benefits and costs of water use.

This terminology and definitions have been adopted by ICID, and will be included in the forthcoming revision of the ICID Multi-lingual Technical Dictionary (MTD) and as much as possible be used in its own publications. ICID recommends adoption of this terminology and definitions to other institutions as well.

NOTES

[1] This paper is essentially a review of the work of others, concluding with recommendations. Drafts have been widely circulated with the ICID ''family'' and valuable comments received from:

Dr Hussein El-Atfy (Egypt), Vice President ICID and Chair, WG-WATS
Dr Frans P. Huibers (Netherlands), Secretary, WG-PQW
M. Gopalakrishnan, Secretary General ICID
Dr E. Gordon Kruse (USA), Member, WG-CD
Dr Vermes Laszlo (Hungary), Member, WG-CROP and WG-ENV
Dr Neil Lecler (South Africa), Member, WG-WATS
Professor Yuanhua Li (China), Member, AC-IPTRID and WG-R&D
Dr Enrique Playan (Spain), Member, AC-IPTRID and WG-R&D
Dr John A. Replogle (USA), Member, WG-R&D
Dr Bryan P. Thoreson (USA), Member, EB-JOUR
Pakistan National Committee on Irrigation and Drainage (PANCID)

The author has also benefited greatly from many discussions and exchanges in the process of compiling these ideas, the most significant being: Rick Allen, Peter Gleick, Marvin Jensen, Andrew Keller, and David Seckler. Bart Schultz has continuously supported this work, and ensured proper consultation and distribution of drafts – as well as providing valuable contributions. Harald Frederiksen has been a constant and patient source of good advice and constructive criticism.

Errors and omissions (and indeed failure to agree with some of these eminent thinkers) remain the responsibility of the author.

[2] This section draws substantially from Jensen (2002).

[3] In Egypt, it makes a great deal of sense to improve ''classical'' irrigation efficiency near the coast, where the drains flow directly to the sea (to the extent that this can be achieved without accelerating saline ingress from the Mediterranean), but very little sense to improve classical efficiency in upper Egypt because all return flows from that area are recovered downstream. This situation is self-evident once the descriptive ''fractions'' approach is applied, but entirely masked by the implicit ''goodness'' of improving ''efficiency''.

[4] David Calderbrook, UK Environment Agency, personal communication.

[5] Decree of the Supreme Court of the United States, no. 108, orig., October term, 2001 State of Nebraska v. States of Wyoming and Colorado on petition for order enforcing decree and for injunctive relief [November 13, 2001] (available at http://www.dnr.ne.gov/legal/nebraska.html).

[6] http://www.iwmi.cgiar.org/wwf4/html/watersituation.htm, viewed 3 April 2006.

[7] The colour scheme has been made more complex by the introduction of ''grey'' water (effluent from municipal and industrial use other than sewerage) and ''black'' water (defined as having dangerous levels of faecal coli). For many rivers, water reaching the sea may have been diverted to irrigation, percolated to an aquifer, been pumped for domestic use, treated in a sewage plant (fully, partially, or not at all) and returned to the river. What ''colour'' classification the water then falls into is neither clear nor useful information.

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[8] Which water depends on the observer – it may be total water consumed by the crop, or water applied through irrigation.

[9] The *intended* use must be clearly identified: in irrigation schemes, it is crop transpiration. Other unintended uses (riparian vegetation, wet areas for migrating birds) may be included as beneficial uses and water provided for these purposes.

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