Improving groundwater resource accounting in irrigated areas : a prerequisite for promoting sustainable use

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Keywords Groundwater resources · Groundwater recharge · Water resource budgets · Agriculture · Irrigation efficiency

Issue of concern

This article has a fundamental underlying concern—that programmes to improve agricultural productivity through the introduction of modern irrigation technology are frequently making the false assumption that increasing 'irrigation (water) efficiency' alone will benefit, or at least not compromise, groundwater resource sustainability (Foster et al. 2000; 2002).

Quite widely, the agricultural development sector promotes major (multi-million dollar/euro) investments in irrigation technology in part as a simple panacea to reverse the continuous decline of water tables, widely observed in more drought-prone agricultural areas of the developing world. This false paradigm is all too often accepted, rather than challenged, by practising hydrogeologists working on groundwater resource development and management in these areas.

The main objective of this article is to highlight (and to provide a ready-reference to) this major policy issue for the groundwater community, because of the importance of the current global dialogue on 'water for food production'—and to indicate a way of viewing the water balance of irrigated permeable soils that provides a sounder basis for managing the groundwater resource-irrigated agriculture nexus.

Received: 13 July 2009 / Accepted: 13 November 2009

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Groundwater resource-irrigated agriculture linkages

Groundwater accounting in the form of a recharge–discharge balance, and especially the detailed breakdown of balance components with their linkages to other components of the water cycle, provides vital information to assess the sustainability of groundwater resources and the potential effectiveness of specific management interventions. In this context, the intimate relationship between groundwater recharge and irrigation water management on permeable soils, during both water distribution and field application, has not received adequate attention.

In more arid climates, groundwater recharge arises incidentally from agricultural irrigation since:

- The distribution of water by irrigation canals and its application at the field level involves potentially high rates of seepage and infiltration respectively, and in groundwater resource balances, such *irrigation return flows* often constitute a substantial component of gross recharge—but one which can be radically modified (in both volume and quality) by changes in irrigation management.
- Where groundwater (rather than surface water) is the principal source of irrigation water, seepage from distribution channels will generally be much less—since waterwells are normally located close to the fields they irrigate, water delivery is much shorter and often piped, and (while excess irrigation at field level will result in recycling a return flow to groundwater) the more precise and local control of delivery volumes results in less frequent over-application.

'Irrigation efficiency': a misleading term

There are various definitions of irrigation efficiency but, in essence, the term is used to indicate the percentage of irrigation water-supply which is actually transpired by the crop under cultivation (although 'irrigation water supplied' has variously been interpreted as that 'abstracted from source', 'delivered to field', 'applied to crop', etc). The term has been widely cited in the agricultural literature for more than 50 years, and is often central to the evaluation of how an irrigation system is performing and of recommendations about what should be improved.

 DOI 10.1007/s10040-009-0560-x

Clearly the purpose of irrigation in agriculture is to increase crop production. The direct implication is that crop transpiration must also increase—because for a given climatic condition and crop type, biomass generation and food production exhibit a close-to-linear relation with crop transpiration (Howell 1990), with just a few exceptions such as wine grapes. And from the farmers' and irrigation engineers' perspective, any water that does not contribute to crop production is considered a 'loss'. These legitimate perceptions explain the origin of the widely used term irrigation efficiency.

However, when looked at from the perspective of a groundwater body or hydrological basin, the situation is very different, since a (variable) part of the farmers 'loss' is returned to underlying groundwater and/or to downstream surface water (depending upon soil profile and irrigation management), and thus is not 'lost' with respect to other users and uses. Moreover, a clearer distinction between the processes affecting water distribution and field application is also required.

Thus, the term irrigation efficiency can be the source of serious miscommunication and misunderstanding at the policy level in both the agriculture and water sectors (Perry 2007). A more rigorous and consistent concept for 'soil-water zone' accounting in irrigated agriculture is much needed (Foster et al. 2009) so as to permit the impacts of change to be assessed and interventions to be prioritised. Here the term soil-water zone (like groundwater zone and surface water zone) is used to indicate a domain in which water is influenced by a characteristic set of processes, recognising that exchange of water between the various domains occurs.

Refining the water balance of irrigated soils

At the field level, water reaching an irrigated permeable soil by whatever process (rainfall or irrigation with surface water or groundwater) splits into two main 'fractions' each with two 'sub-fractions' (Fig. 1), according to interaction between the method of irrigation application and the prevailing soil conditions:

1. A *consumed fraction* which can be further divided into:
    - *Beneficial transpiration* consumed by the crop being cultivated
    - *Non-beneficial evaporation* (including some weed transpiration) from wet soil
2. A *non-consumed fraction* which can be further divided into:
    - *Recoverable seepage* infiltrating as a 'return flow' to a freshwater aquifer
    - *Non-recoverable seepage* infiltrating to a saline aquifer

This approach greatly clarifies soil-water processes and is conceptually much sounder than considering field-level irrigation efficiency and irrigation losses alone, even if its application will require professional judgement to overcome data limitations and to address questions such as:

- Do irrigation returns infiltrate to an exploitable aquifer in a meaningful time-frame under very deep water-table conditions?
- To what extent does capillary rise contribute to crop transpiration in conditions of a very shallow water-table?
- How usable are the more saline irrigation returns (which will vary with the salt-sensitivity of crops being irrigated)?

Estimating the soil-water sub-fractions in any given field situation (Foster et al. 2009) will require information on the irrigation water applied, standard computations of evapotranspiration, and the partition of crop transpiration and evaporation for the corresponding irrigation technology

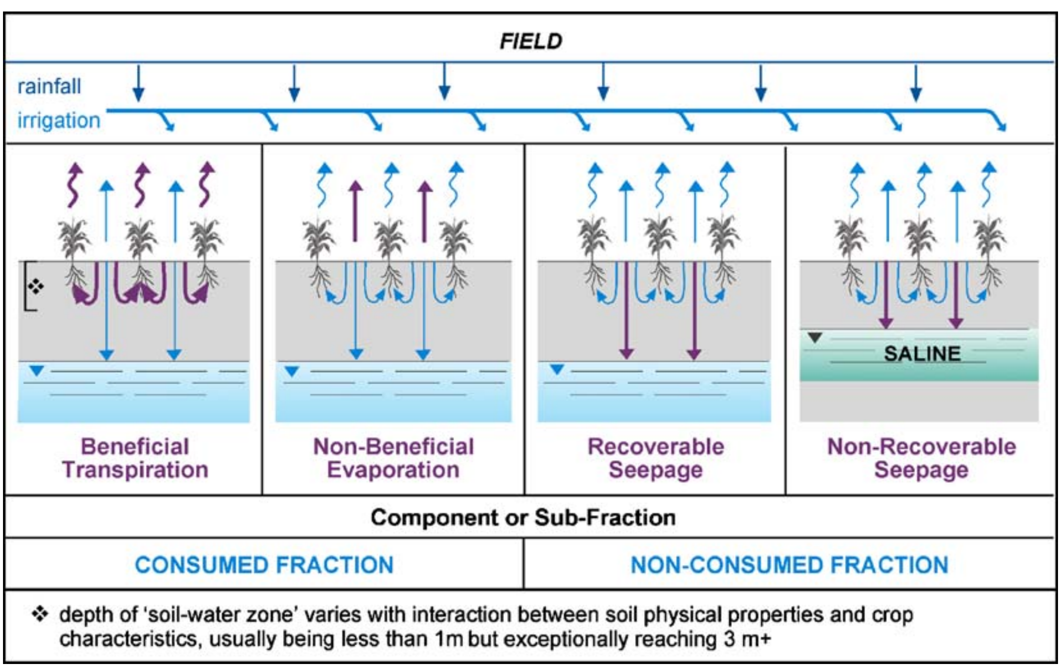


Fig. 1 The utilisation and fate of water applications to permeable soil, and their relationships with groundwater resources and irrigation management

 DOI 10.1007/s10040-009-0560-x

Table 1 Indicative variation of field-level soil-water sub-fractions with irrigation technology

Irrigation technology	Consumed fraction		Non-consumed fraction[b]
	Beneficial transpiration	Non-beneficial evaporation	
Gravity flow to:			
Basin/furrows	Moderate-to-high (40-80%)	Moderate but variable[a]	Moderate (20–30%)
Rice paddy	Low (20–40%)		High (50–70%)
Sprinkler (linear, fixed, pivot, etc)	Moderate but variable	Moderate but variable	Low but variable
Sub-surface pipe with drip	High (85–95%)	Minimal (5–10%)	Minimal (5%)[c]

[a] But with careful management can be substantially reduced

[b] Always the more difficult to estimate and hydrogeological conditions will determine whether this is recoverable

[c] With poor maintenance and operation can increase substantially

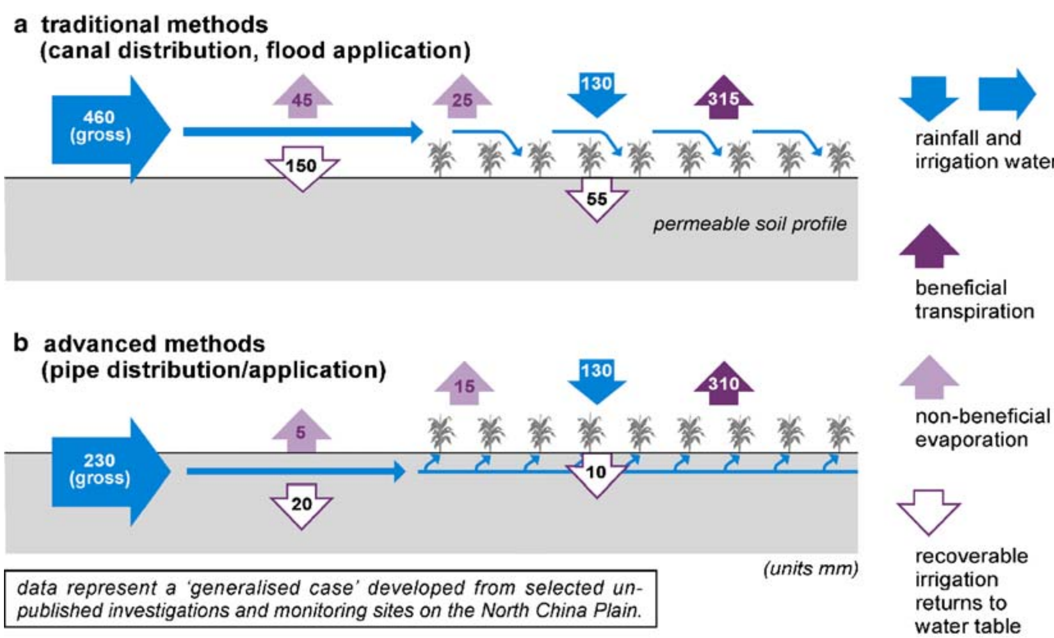
(Allen et al. 1998). The field performance of different irrigation technologies, however, cannot be completely generalised, and the estimates presented (Table 1) should be viewed as indicative of the typical range. Satellite thermal imagery (through SEBAL-type approaches) offers the prospect of measuring total actual evapotranspiration periodically through the cropping cycle and estimating biomass formation to partition transpiration and evaporation (Bastiaanssen et al. 1998).

However the importance of context must not be overlooked, for example:

- Spate irrigation deliberately diverts as much flood runoff to fields as possible so as to provoke deep infiltration as a water-conservation measure (since this water would otherwise be non-recoverable as a result of loss to saline inland basins or to the sea).
- Paddy rice cultivation is unique—the transpired fraction at field level is relatively low but irrigation applications are very high because enough water has to be applied to compensate for seepage and evaporation so as to keep the crop inundated and because of the need for water flows from field-to-field.

In respect of the time basis and spatial framework for soil-water accounting, it should be noted respectively that:

- Monthly data often have to suffice (although the potential influence of high-intensity rainfall events also needs to be appraised from daily rainfall records).



PARAMETER	IRRIGATION TECHNOLOGY	
	Unlined Canals with Gravity Flood Application	Piped Distribution with Pressurised Drip Application
Distribution 'Efficiency'	58%	89%
Application 'Efficiency'	70%	88%
Overall Irrigation 'Efficiency'	40%	78%
Real Water Resource Saving	**12% (55mm)**	
Actual Pumping Energy Saving	**50%**	

Fig. 2 Example of the effect of changing irrigation technology and improving irrigation efficiency on groundwater recharge in an arid region

 DOI 10.1007/s10040-009-0560-x

- Areas of similar cropping regime and soil profile will need to be delineated.

As regards the sub-components of groundwater recharge, the following need to be accounted for:

- Seepage from irrigation canals, accounted separately from seepage during irrigation-water distribution from waterwells
- Infiltration of surface-water irrigation excess to crop requirements at field-level accounted separately from groundwater irrigation excess to crop requirements at field-level

However, conjunctive use of groundwater and surface water for irrigation will complicate the picture. Approximate estimates for non-beneficial evaporation and non-recoverable seepage are also needed to indicate possible interventions to save water resources.

Implications for real groundwater resource savings

Real water-resource savings, which result in more water being available for other users (including environmental flows) and/or for replenishing depleted aquifer storage, can only be achieved by reducing the size of the consumed fractions and/or the non-consumed non-recoverable fraction (Fig. 1), and may be achieved through any combination of the following:

- Reducing non-beneficial evaporation through more targeted and reduced application of irrigation water and/or the use of plastic sheeting or incorporating additional organic material
- Eliminating weeds and any other obvious sources of non-beneficial evapotranspiration
- Switching to cultivation of less water-consuming crops or crop-strains (with shorter growing season, or suited to cooler periods when potential evaporation and transpiration are lower)

However, it will also be essential to at least constrain (and perhaps reduce) the total irrigated area.

An example of the benefits of modernising irrigation technology is shown in Fig. 2—this must be considered a success since the saving in pumping energy was substantial at 50%, but it should be noted that while the overall irrigation efficiency was improved by 38%, the real groundwater-resource savings was only 12% (albeit a useful 55 mm over the area of irrigated crop during the cropping period).

It is obviously not the intention here to suggest that 'inefficient irrigation' should be regarded as good, since some water will usually be lost through unproductive evaporation, power has to be used to pump water that is not consumed in crop growth, and the risk of water pollution from agricultural practices will be higher.

Paradoxically, however, interventions that allow farmers to grow higher value crops per unit of water pumped have the implication of making groundwater use (even against increasing pumping lifts) all the more profitable. And should the farmer irrigate a larger cropped area using water that (from irrigation efficiency considerations) he considers he has 'saved', more water will be consumed by crops and the net groundwater abstraction will increase. Indeed, the reason for a farmer changing irrigation technology is rarely to save water, but more often to seek other (to him) important benefits including:

- Increasing crop-water productivity and profitability through permitting the cultivation of high-value (water-sensitive) crops
- Facilitating labour savings (at least in some instances)
- Saving of electrical energy or diesel fuel for water pumping

Concluding remark

It is a fallacy to believe that investments to improve irrigation technology will alone readily reduce net groundwater abstraction and conserve groundwater resources—and, indeed, without other parallel interventions, the reverse often turns out to be the case. Real groundwater resource savings and more sustainable groundwater use will only be achieved through the concerted efforts of water-resource agencies and agricultural extension services working in close cooperation with irrigation water-users to reduce total evapotranspiration and non-recoverable seepage, whilst maintaining or improving farmer incomes. And a prerequisite for this will be improved water accounting in irrigated permeable soils.

Acknowledgements This paper is a by-product of efforts by Stephen Foster, on behalf of IAH Council 2004–2008, to engage in constructive dialogue with other professional non-governmental organisations in the water sector, focusing on major policy issues where the linkage between groundwater and other facets of water management did not appear to be adequately recognised or correctly diagnosed. In parallel, Chris Perry was promoting wide consultation within ICID on the need to correct ineffective communication on irrigation water management and to improve soil-water terminology. The authors gratefully acknowledge the valuable advice of the *Hydrogeology Journal* Executive Editor, Cliff Voss, and Technical Editorial Advisor, Sue Duncan, on the development of this article as an essay for the Journal .

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 DOI 10.1007/s10040-009-0560-x