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Understanding the Risks of Groundwater Irrigation in Arid Terrains

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Abstract: Groundwater is a vital source of water for crop (and amenity) irrigation in more arid terrains, but one which requires sound understanding and careful management for use to be sustainable. This paper highlights two aspects of irrigated cultivation on permeable soils that have been seriously neglected by agricultural researchers, advisors and water managers and do not figure in practical guidance to farmers on soil and water management – that increasing so-called irrigation efficiency alone will improve groundwater resource sustainability and that salinization of shallow groundwater is an inevitable consequence of irrigation practices.

Key Objectives of Paper: The pressing objective of this paper is to draw the attention of researchers, advisors and managers of irrigated agriculture to two facets of groundwater system behaviour which are especially critical:

- The false assumption that increasing 'irrigation (water) efficiency' alone will benefit groundwater resource sustainability, with major investments in irrigation technology often being promoted erroneously as a panacea to reverse widely observed water-table decline
- Insidious salinization of shallow groundwater by irrigation return-flows is occurring in areas of permeable soils with serious long-term consequences for all waterwell users, but has escaped unnoticed because its impact on crop yields and farmer incomes is not direct and immediate.

Key words:

INTRODUCTION

Groundwater Recharge-Irrigated Agriculture Linkages

Groundwater Resource Accounting: Resource accounting, in the form of a detailed breakdown of balance components with their linkages to other parts of the water cycle, provides vital information to assess the sustainability of groundwater resources and the potential effectiveness of specific management interventions [1]. 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. There is thus an urgent need to adopt a better way of viewing the water balance of irrigated permeable soils and provide a sound basis for managing the groundwater resource/irrigated agriculture nexus.

In more arid climates, groundwater recharge arises incidentally from agricultural irrigation since the distribution of water by irrigation canals and its field application involves potentially high rates of seepage and infiltration and in groundwater resource balances such irrigation return flows often constitute a substantial component of total recharge. Where groundwater is the principal irrigation source excess field irrigation will result in recycling a return flow to the ground, but better control of delivery volumes results in less frequent over-application and seepage from distribution channels will be much less on account of waterwells being close to the fields they irrigate.

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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-supply' has variously been interpreted as that 'abstracted from source', 'delivered to field' or 'applied to crop'. 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 how it can be improved.

Clearly the purpose of agricultural irrigation is to increase crop production. The direct implication is that crop transpiration must also increase — because, for a given climatic condition and crop type (with just a few exceptions), biomass generation and food production exhibit a close-to-linear relation with crop transpiration [2]. And from the farmers' and irrigation engineers' perspective, any water that does not contribute to crop production is considered a 'loss'.

However, when looked at from the groundwater-body or hydrological-basin perspective the situation is very different, since a part of the farmer's 'water loss' is returned to underlying groundwater 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 [3].

Refining the Water Balance of Irrigated Soils: At field level, water reaching an irrigated permeable soil by whatever process (rainfall or irrigation) splits into two 'sub-fractions', according to interaction between the method of irrigation application and the prevailing soil conditions :

- a 'consumed fraction' divided into beneficial transpiration by the cultivated crop and non-beneficial evaporation from wet soil (and some weed transpiration)
- a 'non-consumed fraction' divided into recoverable seepage infiltrating to a freshwater aquifer and non-recoverable seepage infiltrating to a saline aquifer.

This approach clarifies soil-water processes and is conceptually sounder than considering field-level irrigation efficiency alone, even if it requires professional judgement to overcome data limitations and to address the questions:

- 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 very shallow water-table ?

Estimating the soil-water sub-fractions in any given field situation, however, will not be straightforward and requires information on irrigation water applied, computations of evapotranspiration and the partition of crop transpiration [4].

In respect of the time basis and spatial framework for soil-water accounting, it should be noted 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
- Seepage from irrigation-water distribution needs to be accounted separately
- Estimates for non-beneficial evaporation and non-recoverable seepage are needed to indicate possible interventions to save water resources
- Conjunctive use of groundwater and surface water for irrigation will complicate the picture.

Implications for Real Groundwater Resource Saving: 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 [1] and may be achieved through any combination of the following:

- Reducing non-beneficial evaporation through smaller targeted applications of irrigation water and/or the use of plastic sheeting
- Eliminating weeds and any other obvious sources of non-beneficial evapotranspiration
- Switching to cultivation of less water-consuming crops with shorter growing season
- Constraining or reducing the total irrigated area.

An example of the effect of modernising irrigation technology is shown in Figure 1. While this must be considered a success, since the saving in energy for water pumping was substantial (50%), it should be noted that the real groundwater resource savings was only 12% (despite the fact that overall irrigation efficiency was

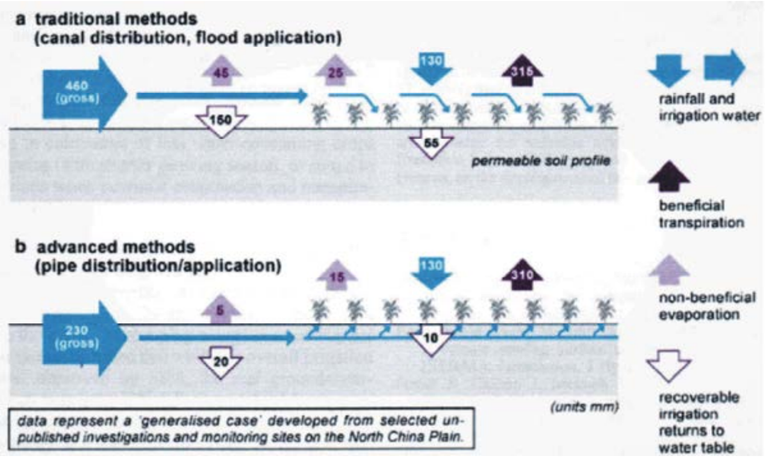


Fig. 1: Typical changes in the water balance of permeable soils caused by changing irrigation technology

improved by 38%). 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. However, interventions that allow farmers to grow higher value crops per unit of water pumped have the implication of making groundwater use more profitable and should the farmer then irrigate a larger cropped area using water that (from irrigation efficiency considerations) he considers '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, facilitating labour savings and making electrical energy (or diesel fuel) savings.

Salinisation of Groundwater Recharge by Irrigation Returns

Process of Salinisation: Rain water has very low total dissolved solids (TDS) and slightly acidic pH — with Cl and Na generally in the range 10–20 mg/L (although higher in coastal zones due to aerosol effects). On coming into contact with the land surface, rainfall acquires Ca and HCO3 and salinity commonly reaches 200–500 mgTDS/L in the rainfall contribution to natural aquifer recharge. Where irrigation is practiced on permeable soils, the dissolved salts in irrigation water are concentrated by evapotranspiration before leaching from the soil profile to groundwater. While irrigation water is usually of the $CaHCO_3$ type, irrigation returns are normally of the NaCl type. It will then be the vertical hydraulic conductivity of the vadose zone that controls the rate of downward penetration of return water and introduces a time-lag before any deterioration in groundwater quality first becomes evident.

The process can be evaluated using a salt-balance approach (Figure 2) and the relative annual salt-concentration factor (CF) for groundwater irrigation estimated on this basis, together with an indication of how this factor varies with irrigation water-use (field-application) efficiency (α) and the crop-type and climatic regime.

It should be noted that irrigation return-flows from a wide variety of crops also often contain elevated concentrations of nitrate, resulting from excessive and/or ill-timed fertiliser applications. While this will cause a serious problem for potable water-supply provision, the co-presence of nitrate acts as a valuable tracer of the agricultural genesis of groundwater salinity.

While the agricultural literature frequently refers to sustainability issues related to irrigation practices, it tends to focus exclusively on the salinization of low-permeability soils due to rising water-table and the consequent negative impact on crop yields [5, 6, 7].

Consequences of Groundwater Salinisation: Groundwater with electrical conductivity (EC) greater than 2, 000 µS/cm has been classified as moderately saline for use in crop irrigation [8]. There is no 'standard conversion' from the (readily-measured) parameter EC to TDS (total dissolved solids or salinity in mg/L), since it varies somewhat with the predominant salts (Na-Cl, $Ca\text{-}SO_4$, $Ca\text{-}HCO_3$, $Mg\text{-}HCO_3$) in solution. An average conversion factor of 0.65 is used here. Whilst it is feasible to irrigate with water of EC up to 5, 000 µS/cm (3, 250 mgTDS/L) for less sensitive

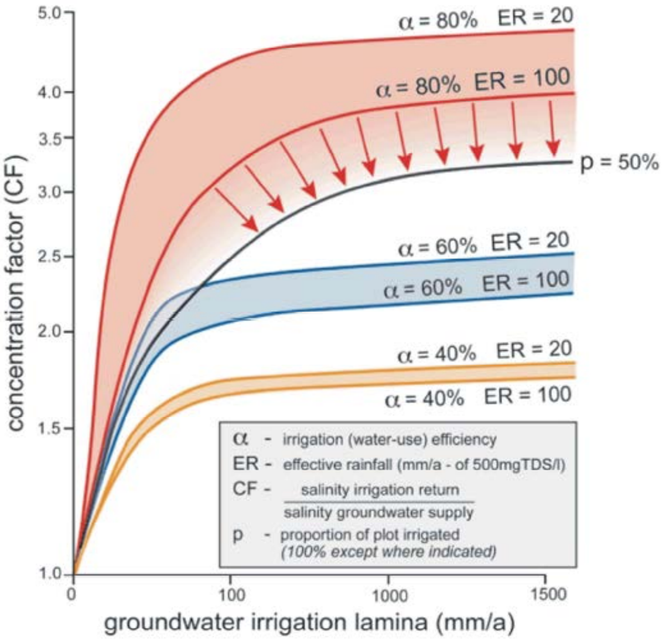


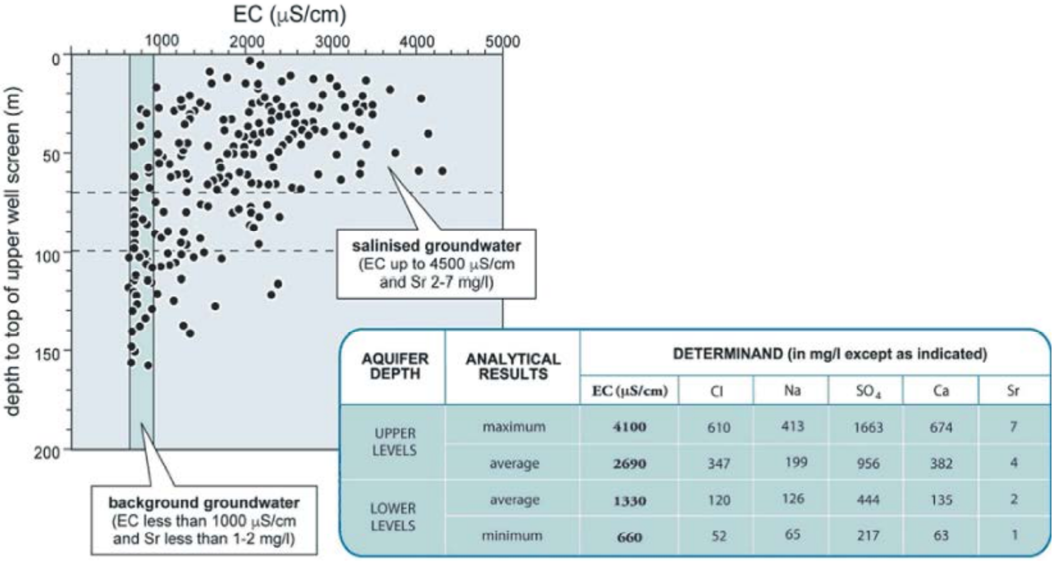
Fig. 2: Variation of concentration of groundwater salinity by irrigation practices (large applications (annual lamina) of groundwater as irrigation occur widely in the more arid climatic regions and the resultant CFs of 2-5 will lead rapidly to serious increases of irrigation return-flow salinity)

crops (e.g. onions), use on more sensitive crops (e.g. some cereals) will impact their growth and reduce productivity. Serious damage will occur to the most sensitive crops, including many vegetables, fruit trees and grape vines [5]. Increasing salinity will also reduce the value of groundwater for public and industrial water supply.

A few examples of groundwater salinization by irrigated agricultural activity are available to support this interpretation [9, 10, 11, 12, 13]. The phenomenon will be compounded where irrigation water with significant salinity is in part used, which will be the case where wastewater is the source.

However, where irrigation is practised on low-permeability soils, the salt will be retained in the root zone, which becomes progressively saline and infertile. Moreover, soil sodicity often increases with increasing irrigation-water salinity leading to a further reduction in soil permeability and breakdown of soil structure [6].

Specific Cases of Groundwater Salinisation: The Carrizal Aquifer of Mendoza-Argentina comprises a thick Quaternary piedmont alluvial formation with a deep water-table (10-70m), occupying an arid Andean palaeo-valley between the present courses of the Mendoza and Tununyan rivers, with an average rainfall of about 180 mm/a and groundwater recharge originating as seepage from a limited stretch of the Mendoza riverbed [14]. During the 1990s the area was discovered to have an exceptional microclimate for export-quality viticulture and fruit production, which created a consumptive water demand of 3–4 mm/day during October–March (totaling 700–800mm/a). The area currently includes about 140 km^2 of irrigated land, mostly served by a major expansion of groundwater use (from more than 600 waterwells), with modern pressurised ferti-irrigation, anti-hail nets and minimal tillage. In the 1960s the salinity of shallow and deep groundwater was 1, 170 and 650 mgTDS/L respectively (EC = 1, 800 and 1, 000 µS/cm), but despite the introduction of a 'groundwater-use restriction zone' in 1997 surveys during 2003 revealed a marked salinity stratification down to 70m depth from 2, 860-1, 960 mgTDS/L (EC = 4, 400-2, 600 µS/cm)(Figure 4) in an area extending progressively from the Mendoza River. Nitrate levels of 20–60 mgNO_3/L compared to <10 mgNO_3/L at depth confirmed the agricultural origin of the salinity, The salinization has resulted in the substitution of onion and garlic cultivation for more profitable viticulture, with a corresponding fall in land values. Key management measures urgently required include diverting more water from the Mendoza River into the Carrizal Valley during periods of peak flow for managed aquifer recharge and



AQUIFER DEPTH	ANALYTICAL RESULTS	DETERMINAND (in mg/l except as indicated)					
		EC (µS/cm)	Cl	Na	SO_4	Ca	Sr
UPPER LEVELS	maximum	**4100**	610	413	1663	674	7
	average	**2690**	347	199	956	382	4
LOWER LEVELS	average	**1330**	120	126	444	135	2
	minimum	**660**	52	65	217	63	1

Fig. 3: Groundwater salinity variation with depth in the Carrizal Aquifer (Mendoza-Argentina) (data mainly for 2003 from Foster & Garduño, [14]) (the salinization of a large part of the aquifer to a depth of about 120m is clearly revealed)

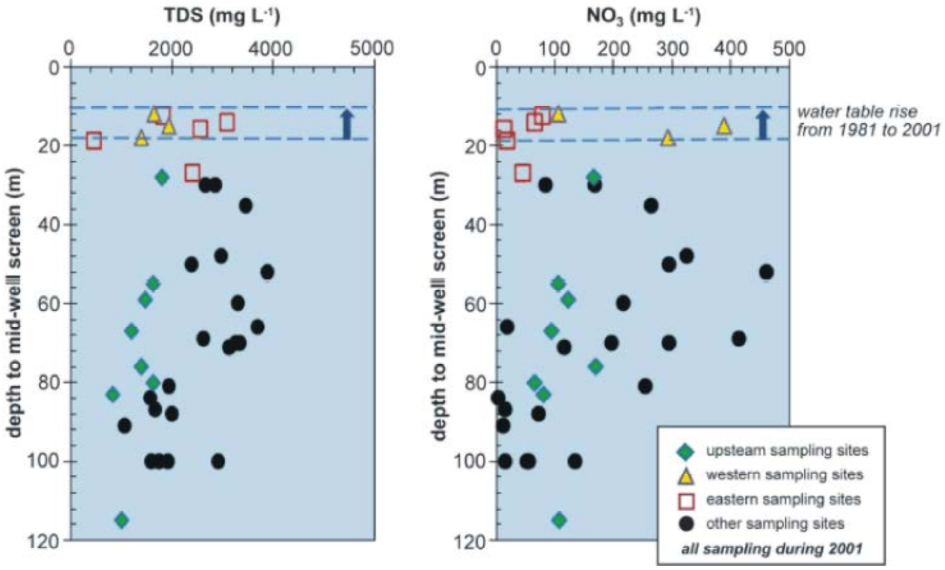


Fig. 4: Groundwater salinity and nitrate variation with depth in the upper aquifer of the Campo de Dalias (Almeria-Spain) groundwater system (after Pulido-Bosch *et al*. [16]) (these are composite profiles from sampling in the shallow Pliocene/Quaternary aquifer – both the salinization of the entire aquifer system to 75+m depth by irrigation return-flows pre-1980 and the rebound of the water-table by about 10m with fresher groundwater recharge are clearly revealed

continuing to constrain consumptive groundwater use by downward adjustment of the licenses of replacement waterwells.

The Campo de Dalias Aquifer of Almeria-Spain lies on a slightly elevated, arid coastal plain with an average rainfall of about 260 mm/a, largely underlain by a phreatic Pliocene/Quaternary alluvial outwash aquifer. It is situated on the southern flanks of the much wetter Sierra de Gador mountains formed by a Triassic dolomitic limestone aquifer which extends highly-confined at depth beneath the plain. During 1965-85 groundwater irrigation expanded rapidly and today there are more than 1, 200 waterwells irrigating about 20, 000 ha (around 65%) of the land surface, which is covered by plastic greenhouses with ‘engineered soils’ using hydroponic cultivation to produce tomato, pepper, cucumber, eggplant, courgettes, green beans, melon and watermelon, mainly for the export market [12]. The intensive groundwater-based irrigation and extensive greenhouses have completely modified the local groundwater regime. The artificial well-drained soils allow excess irrigation to leach accumulated salts (with 75% of farmers applying 2 lamina of 30–60mm for this purpose), rainfall on greenhouses being directed to soakaways and large manure applications (2, 300–4, 600 kgN/ha on greenhouse construction and 600–1, 700 kgN/ha on each crop) leading to an increase of groundwater salinity down to 70m depth from <1, 200 mgTDS/L to 2, 000-4, 000 mgTDS/L (Figure 4). This has led to the abandonment of many waterwells in the shallow aquifer and use of the deep Triassic Dolomitic aquifer, resulting in recovery of the shallow water-table and the creation of a sizeable brackish-water lagoon 1[5]. Elevated groundwater nitrate concentrations (100–400 mg NO_3/L) confirm the presence of saline irrigation-water returns in the upper aquifer and their stable isotope (^{15}N & ^{18}O) composition suggests that most is manure-derived [16]. The ‘freshening-up’ of the uppermost 25m of the shallow aquifer can be attributed to a reduction in irrigation return-water salinity from use of the deep aquifer and also to some artificial recharge from greenhouse drains.

CONCLUDING DISCUSSION

Land and Water Management Needs: It is a fallacy to believe that investments to improve irrigation technology will alone reduce net groundwater abstraction and conserve groundwater resources. 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 water-resource agencies and agricultural extension services working in close cooperation with irrigation water-users to reduce total evapotranspiration and non-recoverable seepage, whilst endeavouring to maintain farmer incomes. A prerequisite for this will be improved water accounting in irrigated permeable soils.

The persistence and complexity of problems arising through groundwater recharge salinisation from irrigated agriculture are such that they can only be properly addressed through integrated land and water management. The implementation of essential management measures will require awareness-raising and capacity-building. Where groundwater is the primary source of irrigation water, the aquifer system will often be the ‘ultimate sink’ for salinity accumulation. In such circumstances, more complex measures will be needed to ‘freshen-up’ the groundwater system such as :

- Reducing the overall consumptive use of groundwater to conserve natural throughflow and drainage, by reducing annual cropping intensity (for example by not growing a summer crop)
- Adopting greenhouse cultivation, which substantially reduces crop evapotranspiration
- Down-sizing the groundwater-irrigated area by eliminating any crops of lower market value
- Increasing freshwater recharge, by capturing local storm-water run-off to recharge lagoons.

Essential Monitoring Actions: Water resource agencies, in close collaboration with their agricultural counterparts, need to evaluate water and salt balances at aquifer sub-catchment level periodically, to assess the seriousness of potential problems and to guide possible management interventions. It is only through improved measurement that negative trends can be identified early and appropriate management interventions introduced.

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