# Conjunctive groundwater use: a 'lost opportunity' for water management in the developing world?

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## Conjunctive groundwater use: an important but neglected topic

Conjunctive groundwater use with surface-water resources has only occasionally been considered in the hydrogeological literature and at scientific conferences (e.g. Bredehoeft and Young 1983; Sahuquillo 2002), although *in terms of practical water management* it represents one of the most important responses to improving drought water-supply security and for long-term climate-change adaptation, and *in terms of underpinning science* its design requires a refined understanding of resource interconnectivity (both naturally and perturbed by irrigation works or practices) and of aquifer salinisation processes.

The aim of this essay is to provide an overview of current conjunctive use in the developing world for both irrigated agriculture and urban water-supply, and to highlight the great potential that planned 'conjunctive management' has as a climate-change adaptation strategy. It is primarily relevant to larger alluvial plains, which often have important rivers, large-scale irrigation systems and major aquifers in close juxtaposition—although the potential for conjunctive management can be present in a wider range of settings.

There is no rigorous definition for 'conjunctive use'; however, for the present purpose it is proposed to consider only situations where *both* groundwater and surface water are developed (or co-exist and can be developed) to supply a given urban area or irrigation canal-command—although not necessarily using both sources continuously over time nor providing each individual water user from either source.

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Adopting this rather narrow definition excludes consideration here of artificial recharge of aquifers with surface runoff or by rain-water harvesting (without direct supply from the surface-water source), use of groundwater pumping to support river baseflows (without direct supply from water wells) and catchment-scale integrated water-resources management embracing everything from flood protection to wastewater reuse (because of insufficient finance as yet to apply this in the developing world)—although it is recognised that all such techniques can play an important role in water-resources management.

A key characteristic of conjunctive use is that it deploys the large natural groundwater storage associated with most aquifers to buffer the high flow variability and drought propensity of many surface watercourses (Foster et al. 2010a), and is thus capable (at varying levels of efficiency) of achieving: (1) much greater water-supply security—by taking advantage of natural aquifer storage, (2) larger net water-supply yield than would generally be possible using one source alone, (3) better timing of irrigation-water delivery—since groundwater can be rapidly deployed to compensate for any shortfall in canal-water availability at critical times for crop growth, (4) reduced environmental impact—by counteracting land water-logging and salinisation, and (5) excessive river-flow depletion or aquifer overexploitation. These benefits have been the driving force for spontaneous conjunctive use of shallow aquifers in irrigation-canal commands worldwide.

## Improving irrigation-water productivity

### *Spontaneous conjunctive use: a widespread reality*

Groundwater irrigation has developed widely in numerous irrigation-canal commands, usually on a spontaneous basis but sometimes encouraged by government subsidy. In large areas of the Indo-Gangetic Plain (in the Indian States of Punjab and Uttar Pradesh), over 70% of irrigation water supply is derived from water wells, albeit that a proportion of the groundwater resource itself originates as irrigation-canal seepage (Garduno and Foster 2010). In Pakistan, less than 50% of water applied in various large-scale irrigation commands comes from the canal system, and most of the rest comes from water wells (Foster et al. 2010a). In the Tadla Valley of Morocco, water wells widely provide more than 40% of on-farm water deliveries (Steenbergen and El Haouari 2010) and, around the irrigation-canal commands of Mendoza State in Argentina, groundwater has been the key



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to improving water-security for high-value irrigated agricultural production (Foster et al. 2010a).

Spontaneous conjunctive use usually arises in situations where canal-based irrigation commands are: (1) tied to rigid canal-water delivery schedules and unable to respond to crop needs, (2) over-stretched with respect to surface-water availability for dry season diversion, (3) inadequately maintained and unable to sustain design flows throughout the system, and (4) poorly administered, allowing unauthorized or excessive off-takes. Any combination of these leads to inadequate surface irrigation-water service levels in a significant part of the canal system. Thus, private water-well drilling usually proliferates, and the resultant groundwater use is usually characterised by higher water productivity (in terms of kg crop per ha/m$^3$ or US$ income per ha/m$^3$), despite (or perhaps because of) the unit water-supply cost to the user being much higher (Foster et al. 2010a). However, this essentially spontaneous (unplanned, unregulated and unmanaged) groundwater use sometimes results in aquifer depletion to water-table levels that complicate the deployment of low-cost ground-level irrigation pumps and/or that induce saline groundwater encroachment. In contrast, there continue to be many irrigation-canal commands where surface-water use and losses are excessive, causing land water-logging and depressed agricultural productivity.

## Planned conjunctive management: major potential but significant impediments

There is a need to move from spontaneous conjunctive use to planned conjunctive management in irrigation canal commands—whilst recognising that there will be an upper limit on how much groundwater can be abstracted for consumptive use in agricultural irrigation (for any given hydrogeological setting and surface-water delivery scenario), related to the average recharge rate over the entire area under consideration. The key issue is to find a balance of groundwater use which avoids long-term water-table decline, whilst also countering rising water tables and reducing the menace of land water-logging and soil salinisation. Water allocation in conjunctive management areas needs to be on an 'integrated basis', recognising that surface water and groundwater are usually hydraulically linked in alluvial aquifers. This is not straightforward, even in more developed economies (e.g. Murray-Darling Basin Authority 2010), for a number of historical factors, including the reality that canal-water entitlements are often 'area based' (not 'volume controlled').

The potential for, and dynamics of, conjunctive use in agricultural irrigation vary considerably with geomorphological position (and the related shallow hydrogeology) on alluvial plains (Fig. 1). They are also influenced by such factors as current average rainfall and paleo-climatic history. In some instances conjunctive use encounters increasing groundwater salinity, which if not adequately diagnosed and controlled will result in a serious decline in agricultural productivity and concern about drinking-water security. Such salinity threats (Fig. 1) arise from: (1) classic encroachment of saline groundwater due to excessive abstraction of fresh groundwater, both in arid inland basins and coastal areas, (2) leaching of salinity from soil profiles across irrigation areas with accumulation at the water table, due to the first habilitation of arid soils and/or fractionation of salts during efficient irrigation, (3) extensive naturally saline groundwater in hyper-arid areas, except where infiltration from surface watercourses and irrigation canals forms freshwater lenses, and (4) rising water table due to excessive canal seepage and/or field application in head-water areas (where groundwater is not used), leading to land water-logging and soil-water salinisation.

The lining of primary and secondary irrigation-canals will be a high priority on arid alluvial plains if the phreatic aquifer is naturally saline, since canal seepage will be a non-recoverable loss contributing to rising water-table and soil-water salinisation. The same applies to low-lying humid alluvial plains with shallow fresh groundwater systems, since excessive canal seepage will contribute to land water-logging and secondary soil salinisation. However, in marked contrast, on highly permeable alluvial terraces and pene-plains (especially in arid areas), secondary and tertiary canal systems are often found only to carry water for a few days per year, and the majority of irrigation users depend entirely on water wells. However, this is still regarded as conjunctive use since canal seepage is responsible for the greater part of aquifer recharge and any attempt to line these canals to 'save water' for use in other areas could be very detrimental to existing conjunctive use (Fig. 1).

It must also be emphasised that (for all unconfined aquifers) an important component of total groundwater recharge will actually be from irrigation returns (irrigation-canal seepage and excess application at field level)—and thus it is essential to avoid 'double water-resource accounting' (Garduno and Foster 2010). Any measures taken to improve irrigation water distribution and application efficiency are likely to impact on groundwater-resource availability. Detailed design consideration will also need to be given to water-well interference during extended drought, to potential salinity issues (and how many cycles of irrigation reuse are feasible) and to the impact of upstream groundwater use on downstream dry-weather river baseflow.

Integrated numerical modelling of irrigation-canal flows, groundwater use and aquifer response, soil-water status and crop water-use is a great aid to evaluating the benefits of planned conjunctive management (by varying the spatial and temporal use of groundwater and radical rescheduling of surface-water distribution and allocation). Agricultural production can be notably increased (through improvements in cropping intensity and water productivity) without compromising groundwater-use sustainability. A good example is found in Uttar Pradesh, India, where the Jaunpur Branch on the Gangetic Alluvial Plain has been subject to detailed study (Foster et al. 2010a). In the most ambitious of planned conjunctive-use schemes, abstraction from the respective sources can be optimised, not only with respect to surface-water-resource availability and distribution, but also to reducing evaporative losses in surface-water storage reservoirs and minimising actual energy costs of irrigation (in terms of kWhr/ha).



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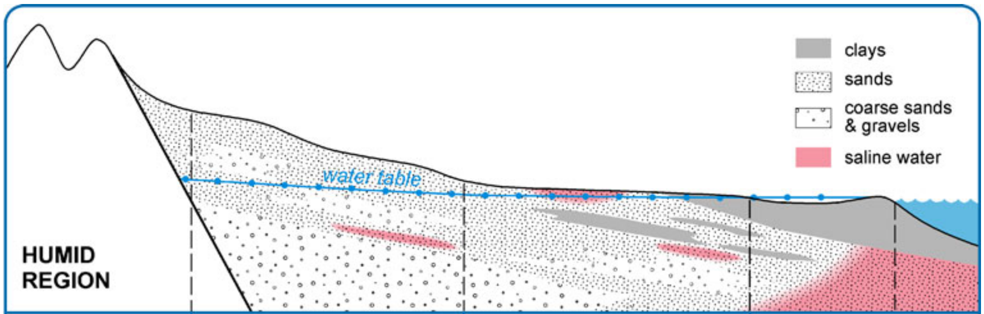


| *ALLUVIAL SETTING* | OUTWASH & PENE-PLAIN | FLOOD PLAIN | COASTAL PLAIN |
|---|---|---|---|
| ***Hydrogeological Conditions*** | unconfined high-yielding aquifer with increasingly deep water table but rapid vertical recharge | multi-layered aquifer with shallow water table and moderate waterwell yields but with some 'rejected recharge' | confined aquifer with very restricted vertical recharge and reducing effective thickness |
| ***Water Resource Management Implications as in Humid Regions*** | much care needed to avoid 'double-accounting' due to infiltration of surface water via irrigation systems | poorly-managed surface water irrigation results in soil water-logging/ salinisation; river baseflows used for irrigation can be greatly reduced by 'upstream' consumptive groundwater irrigation use | aquifer highly vulnerable to saline water intrusion on intensive exploitation and reversal of natural hydraulic gradients |
| ***Water Resource Management Implications as in Hyper-Arid Regions*** | high soil-profile salinity under natural vegetation mobilised when irrigated cultivation introduced | groundwater at depth naturally saline with freshwater restricted to lenses beneath major rivers/irrigation systems | surficial aquitard may also contain saline water which can seep downward |

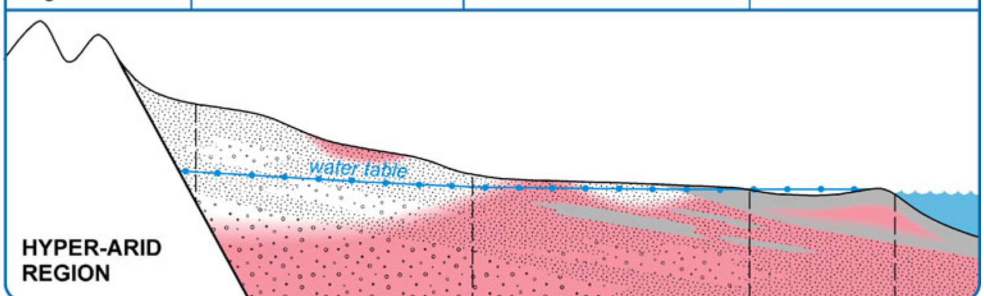


**Fig. 1** Schematic long-profile of a typical alluvial groundwater system in a humid region detailing the variation in groundwater-surface water connectivity and salinisation hazards

The impediments to promoting more rational and better planned conjunctive use in established irrigation-canal command areas can be significant and include (Foster et al. 2010a): (1) socio-political dominance of farmers in areas excessively-endowed with surface water, who refuse to reduce canal intakes so as to allow a greater proportion of available flow to reach marginal areas, (2) inadequate understanding of conjunctive use and the potential role of groundwater by water-resource and irrigation engineers, since it is poorly taught in academic engineering centres, (3) split responsibility for surface-water and groundwater development and/or management, with organisations and agencies which tend to 'mirror' historical irrigation water-supply realities and perpetuate the status quo, (4) lack of rural electrification and reliable electricity supplies for groundwater pumping in some major irrigation-canal command areas, and (5) inadequate water-resource and supply charging systems with a large cost differential (as felt by users) between groundwater and surface water for irrigation because of the tradition of providing canal-water at highly-subsidised cost. These impediments must be overcome by a long-term campaign of education about the risks of water-logging and salinisation, and collateral benefits of groundwater pumping—with the introduction of revised water allocation criteria incorporating incentives for balanced groundwater use. Water-use administration can be delegated (within a sustainable and transparent framework) to appropriate irrigation water-user associations (IWUAs) in which groundwater-only users are also federated.

## Improving urban water-supply security

A second major area of application for conjunctive water management is in urban water-supply. A large number of fast growing cities depend on a combination of surface-water storage and public and/or private waterwell development. The forms of conjunctive use for urban water supply most commonly encountered in the developing world amount to a piecemeal engineering strategy in which either (1) water wells have been drilled by (or for) the municipal water utility on an ad-hoc basis in newly constructed suburbs to meet their water demand at lowest possible capital cost independently of the pre-existing utility river-intake system—Recife, Brazil (Foster et al. 2010b), and Lucknow, India (Foster et al. 2010a), are good examples of this practice, or (2) surface


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water has been imported from a major new distant source to reduce dependency on water wells in the older parts of a city because of excessive exploitation and/or pollution fears—the situation 15 years or so ago in Bangkok, Thailand (Buapeng and Foster 2008), and Lima, Peru (Foster et al. 2010a). Another frequent form of unplanned and sub-optimised conjunctive use is where private domestic and commercial users in urban areas construct water wells for in-situ self-supply, frequently as a 'coping strategy' when confronted with unavailability, poor levels or high prices of utility water-supply (Foster et al. 2010a).

However, today some examples exist of more integrated schemes (e.g. Lima and Bangkok) where the key to optimal development of conjunctive use is not only source development but also engineering of a mains-water-distribution system so as to allow the majority of users to be supplied from different sources at different times (Buapeng and Foster 2008; Foster et al. 2010a)—although one source may not always be capable of completely substituting the other for capacity reasons and it is the balance between the two sources that is varied.

Common impediments to the full development of conjunctive use for urban water-supply include: (1) urban water engineers often tending to look only for operationally simple set-ups such as major surface water-sources and large treatment works, rather than more secure and robust conjunctive use solutions, (2) inadequate understanding of the extent of private in-situ self-supply with groundwater from shallow aquifers, its benefits and its risks, (3) urban water-service utilities often being politically or institutionally constrained from proposing the development and protection of urban well fields in favorable areas (where high yields and good quality can be obtained) outside the city's municipal limits, (4) split responsibility for surface-water and groundwater management (and also development) between provincial or state or national governments and municipal authorities, in some cases under the control of different political parties, and (5) lack of sound and intelligible public information about conjunctive use opportunities, because of the absence of a 'communication unit' at a high level in water-resource agencies.

All such impediments need to be confronted by state or provincial water-resource agencies engaging closely with local municipal authorities and the corresponding water utility; in some cases with national water policy involvement. Systematic studies need to be undertaken of technically sound and administratively reasonable options for fully integrated conjunctive use that would be in the long-term interest of urban water-supply security. In so doing, an important corollary that must be addressed is making best use of the growing wastewater resource being generated from urban areas.

## Concluding message

The evolution to more planned conjunctive use of groundwater and surface-water resources offers great potential for increasing water-supply security in both irrigated agriculture and urban water-supply across the developing world, especially on large alluvial plains which are often major centres of population and economic development. However, the institutional dimension of conjunctive use management is significantly more complex than where surface water or groundwater alone is the predominant water-supply source. In many alluvial regions, the authority and capacity for water-resources management are mainly retained in surface-water-oriented agencies, because of the historical relationship with the development of irrigated agriculture (from impounding reservoirs or river intakes and major irrigation canals). This has led to little interest in complementary and conjunctive groundwater management. Some significant reform of this situation will be essential—such as strengthening the groundwater-resource management function and/or creation of an overarching and authoritative 'apex agency'. Hydrogeologists should become more proactive in arguing the case for conjunctive water-resource management in such situations, and for the institutional changes which can help facilitate its promotion.

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