International Association of Hydrogeologists

Strategic Overview Series

GLOBAL CHANGE & GROUNDWATER

KEY MESSAGES

- groundwater provides an excellent 'buffer' against the climatic variability of surface-water supplies (thereby supporting climate-change adaptation), because of the storage reserves of aquifer systems
- the impacts of human-induced global warming on groundwater remain uncertain, but are a cause for concern given their rapid rate of change compared to natural climate oscillations
- palaeo-environmental records reveal that major changes in groundwater systems occurred as a result of 'natural climate change' over the past 10,000 - 500,000 years, and that measurable oscillations in the rate and salinity of recharge have occurred in the last 50-100 years
- some anthropogenic land-use changes have already caused large impacts on groundwater, with intensification of agricultural production in response to growth of global population and of food demand, being the largest driver
- depletion of groundwater resources since the 1950s, primarily by waterwell pumping for irrigated agriculture, has led indirectly to a net transfer of water from land to sea, contributing to sea-level rise

How do global changes in climate and land-use relate to groundwater ?

Groundwater (contained in sediments and rocks) constitutes the planet's predominant reserve of fresh water, commonly with storage times from decades to centuries and millennia. Groundwater resources thus provide an excellent 'buffer' against the effects of climate variability on surface-water supplies, because of the generally large and widely-distributed storage reserves of aquifer systems. But questions arise as to how naturally resilient are groundwater reserves themselves to global change, and whether we are doing enough to help conserve and protect them.

Groundwater flows into and out of aquifer systems in the subsurface, with their storage being augmented or depleted as a result of changes to this balance, which varies temporally and is controlled by both natural conditions and human activities, with :

- inflows in recharge areas – mostly from infiltration of excess rainfall and surface-water bodies naturally and as a result of agricultural irrigation practices (and more locally of seepage from urban water-main leaks and wastewater disposal)

A SAHARAN OASES - FORMED BY DISCHARGE OF GROUNDWATER STORED IN LARGE AQUIFER SYSTEMS FOR 10,000 - 1,000,000 YEARS

This Series is designed both to inform professionals in other sectors of key interactions with groundwater resources and hydrogeological science, and to guide IAH members in their outreach to related sectors.

- outflows – by natural discharges in springs and to watercourses, wetlands and lagoons, and by pumping from waterwells.

Prior to large-scale anthropogenic activity (pre-1850 at earliest and pre-1950 in many regions), human impact on groundwater systems (in terms of modification, abstraction and pollution) was tiny in comparison to the available resource. Most aquifer systems were in balance between recharge and discharge, and natural groundwater quality was generally excellent. But increased pressures have been put on groundwater from population growth, agricultural intensification, urbanisation/ industrialisation and climate modification.

The focus of this strategic paper is to review present understanding of the large-scale impacts of changing climate and anthropogenic land-use on our groundwater resources, in terms of both their quantity and quality[1]. In the future when taking stock of the social sustainability of human activities, it will be essential to consider carefully the depletion and degradation of groundwater, and in terms of their impact on environmental capital.

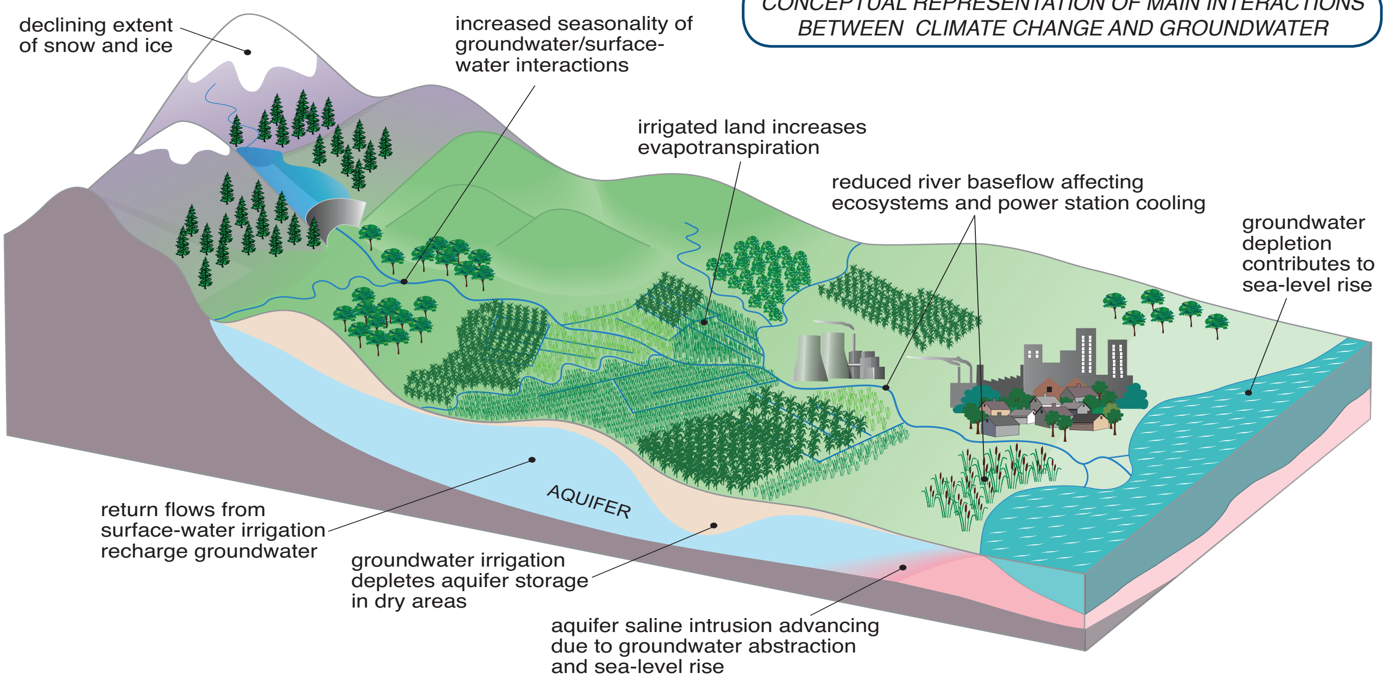
(1) other briefs in this Series have addressed the issues of agricultural production (Food Security & Groundwater), urbanisation (Resilient Cities & Groundwater) and industrial pollution (Human Health & Groundwater)

What is the likely effect of global warming on groundwater ?

The estimation of contemporary (and prediction of future) groundwater recharge rates is of fundamental significance when considering resource sustainability – in areas of increasing aridity rainfall recharge will become less significant than indirect recharge from surface runoff and incidental recharge from human activity.

There remains significant uncertainty over the precise effect of global warming on groundwater recharge in different regions. On one hand, higher ambient temperatures will trigger fewer but more intensive rainfall and increased recharge may occur (offsetting increased evapotranspiration), such that in some fissured (low-storage) aquifers the water-table may rise to levels higher than previously recorded causing damage to property and crops. On the other hand, fewer but heavier rainfall events will deplete soil moisture, and could lead to soil erosion and gullying, or to soil compaction, which will reduce infiltration capacity and groundwater recharge.

CONCEPTUAL REPRESENTATION OF MAIN INTERACTIONS BETWEEN CLIMATE CHANGE AND GROUNDWATER



It is important to note that the 'natural rates' of climate and land-cover change regularly experienced over the past 400,000 years were slower than those of human-induced change. The smallest-predicted rate of global warming is about 10 times greater than has occurred previously, which raises concern about its effect on groundwater recharge, especially to low-storage aquifers on which millions depend in tropical regions. Nevertheless, given the storage inertia of many large aquifers only sustained climate change will begin to deplete available groundwater reserves.

In contrast increased groundwater abstraction and some major land-use changes, are capable of exerting a major impact on both groundwater recharge and quality within decades. Thus in looking forward the combined impacts of global warming, land-use change and groundwater exploitation must be considered.

What does the palaeo-environmental record reveal about the influence of natural climate variability on groundwater ?

The long-term response of groundwater systems to natural climate variability, independent of human activity, can be identified from palaeo-environmental evidence. In their natural state most groundwater systems and their land-cover have adapted to major climate-change cycles during the past 200,000 years or more. And in the short-term for some semi-arid regions (like the Sahel), isotope and chloride profiles of 'unsaturated zone moisture' above aquifers reveal that over the past 50-100 years there has been marked oscillation of groundwater recharge rate and salinity caused by drought-cycles.

Moreover, groundwater from many large aquifer systems in what today are the most arid parts of the world reveal that most groundwater was recharged from 5,000 to 500,000 years or more ago, during past episodes of cooler and wetter climate (eg. the Nubian Sandstone aquifer in the Sahara) — and in these areas 'unsaturated zone profiling' indicates that little rainfall recharge (<5 mm/a) has taken place subsequently. Since contemporary recharge is responsible for only a tiny fraction of groundwater in such aquifers their resources can be considered as 'non-renewable', and the water-supplies they provide highly resilient to current climate variability. However, in the end, their use will be time-limited and as such deserves careful consideration – at present the countries most dependent on such resources are Libya, Saudi Arabia and Algeria, with significant use also in Australia, China, Iran, Egypt, Tunisia, Botswana, Mauritania, Peru and the USA.

In which ways does groundwater use contribute to global change ?

Groundwater has been a vital source of domestic water-supply and agricultural irrigation throughout human history. But intensive groundwater abstraction commenced from the 1950's following major advances in geological knowledge, waterwell drilling, pump technology and rural electrification. Globally groundwater withdrawals are still increasing, having reached 900 km^3/a in 2010, and provide about 36% of potable water-supply, 42% of water for irrigated agriculture and 24% of direct industrial water-supply. Withdrawal intensity is highest over much of China, India, Pakistan and Iran, and parts of Bangladesh, Mexico, the USA, the EU, North Africa and the Middle East. Estimates of rates of permanent storage depletion range from 100-145 km^3/a during 2000-08[(2)].

Groundwater resource depletion contributes indirectly to global sea-level rise (with its serious consequences for coastal areas), by creating a transfer of water from long-term terrestrial storage to circulation in the surface hydrosphere. This process is subject to uncertainty because of inherent imprecision in long-term aquifer water-balances, the average unit drainable storage of

(2) Doell et al (2012), Wada et al (2016)

depleted aquifers and the proportion of extracted groundwater remaining in the local micro-climate. Recent estimates range up to 0.6 mm/a, with a value of 0.3 mm/a (equivalent to 106 km^3/a water transfer or 18% of current sea-level rise) being most likely during 2000-08 [(3)].

Which land-use changes are causing major impacts on groundwater resources ?

Every land-use practice, and land-use change, has a water resource imprint. This is particularly important for groundwater because some land-use changes can have long-lasting effects that are extremely costly to mitigate. The more significant changes for groundwater include clearing natural vegetation and forests, converting pasture to arable land, extending the frontier of irrigated agriculture, intensifying both dryland and irrigated agriculture, introducing biofuel cropping, reforestation/afforestation with commercial woodland - and, of course, urbanisation[(1)]. These various land-use practices leave different signatures :

- on recharge quality – in some instances resulting in diffuse groundwater pollution irrespective of climate conditions
- on recharge rates and salinity – especially significant under more arid conditions.

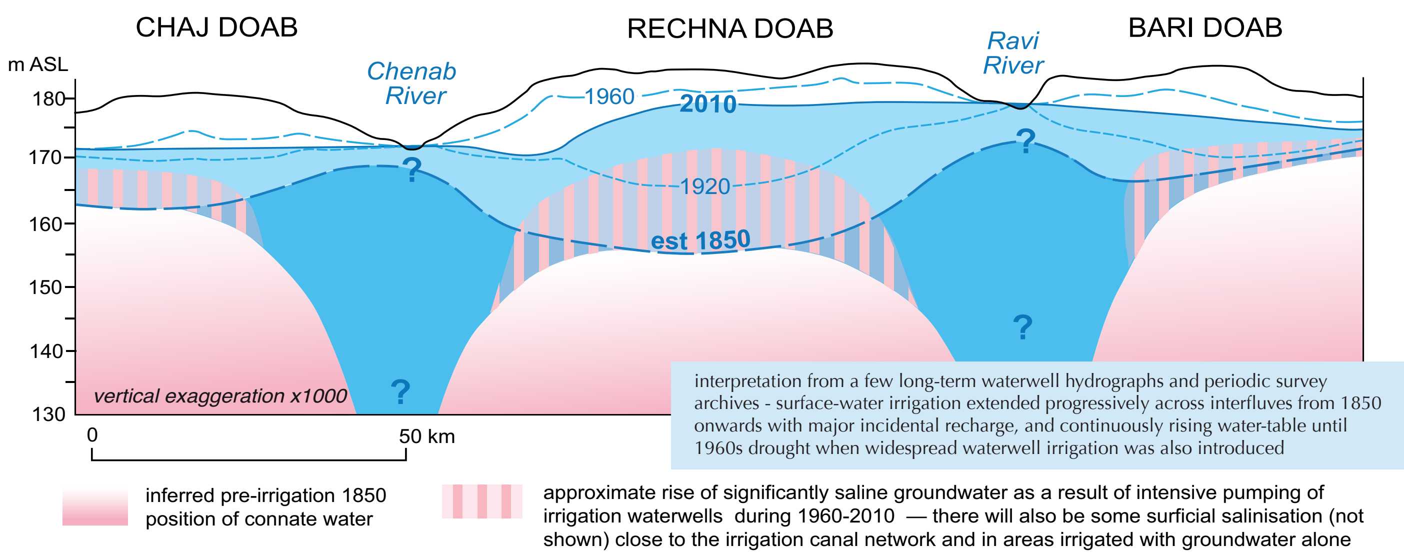
(3) Konikow (2011), Wada et al (2016)

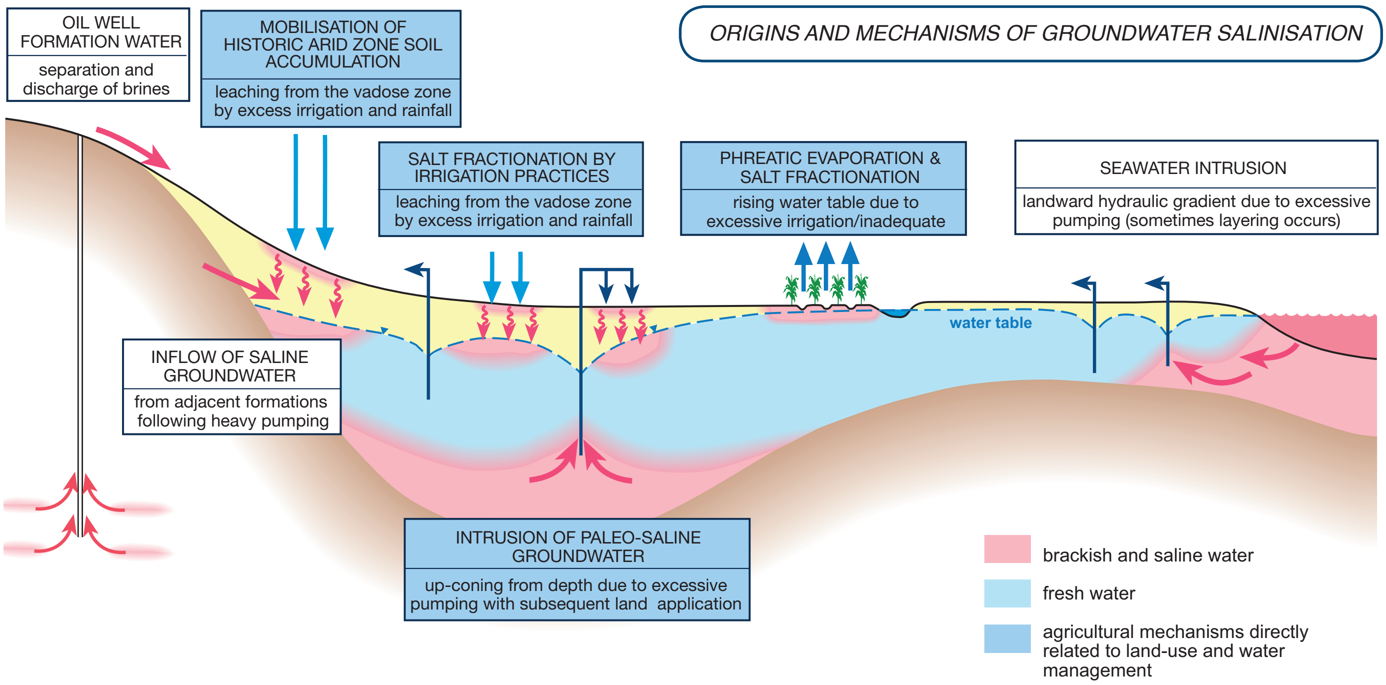
Over the past 250 years, more than half the global ice-free land has been modified by human activity, mainly conversion of native forest to arable land (70%) and pasture land (30%) [(4)]. Up to 1950 the rate of conversion was higher than population growth, and occurred mainly in Asia, Europe, and North America. Latterly global conversion has slowed and most deforestation is now occurring in tropical America and Asia. These changes result from population growth and increasing food demand, but it is not a simple relationship. Since 1960 global population has more than doubled, but food consumption tripled with only a 10% expansion of agricultural land (since increased production came from intensifying cropping and improving crop yields).

Amongst major land-use change, vegetation clearing and extending irrigated agriculture (using imported surface-water) have the greatest influence on groundwater – with the latter significantly increasing recharge and changing water quality because excess irrigation-water infiltrates into shallow aquifers. But intensifying irrigated vegetable and fruit cultivation using 'precision irrigation' (such as pressurised drip and micro-sprinkler systems) can markedly decrease recharge rates and increase recharge salinity.

(4) Foster & Cherlet (2016)

SCHEMATIC REPRESENTATION OF CHANGES IN THE INDUS PLAIN GROUNDWATER SYSTEM OF MIDDLE PUNJAB DURING 1850-2010





Many graphic examples exist, from widely-varying climate types of the major impact of agricultural land-use changes on groundwater :

- the introduction of large-scale surface-water irrigation in some semi-arid areas has led to major accretion of groundwater over decades from the mid-19th century, most notably in the Pakistan & Indian Punjab
- in Mediterranean Europe and the USA the development of intensive horticultural activity for fruit and vegetable production has resulted in serious groundwater pollution with nitrates and persistent insecticides
- in dryland farming, widespread conversion of extensive pasture land to intensive cereal cultivation from the 1950s in Western Europe caused a marked change in groundwater recharge quality with diffuse pollution by nitrates and persistent herbicides.

Globally a steadily increasing area of agricultural land (currently 1.6 million ha) is impacted by salinisation – off-setting much of the gain in agricultural productivity elsewhere [4]. Many of the causes are groundwater related :

- direct evaporation from shallow water-tables, often associated with inefficient irrigation using imported surface water in areas of inadequate natural drainage
- natural salinity being mobilised from depth in groundwater systems through uncontrolled waterwell construction and pumping, and from the leaching of saline sub-soil following clearing of natural vegetation
- soil salinity build-up when irrigating with mineralised groundwater, which is subsequently leached to shallow aquifers.

Understanding the linkages between agricultural land-use and groundwater is an essential basis for integrated water resources management, and although these linkages have long been recognised they have not yet been widely translated into land management policy and practice.

Today, large-scale forces, especially globalisation of commodity markets, have become the main drivers of land-use change, with certain national and local factors attenuating or amplifying their effects. They influence not only the land-use choices of millions of small producers but also those of large international (private and state) investors. Large-scale agricultural land projects in the less-developed countries are estimated to have involved at least 36 M ha of land since 2000. Where large-scale land deals occur without

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open and informed consent of present local users, they are called 'land grabbing', and such land acquisitions often also entail preferential (and not fully investigated) access to groundwater.

In low-income countries, there is a pressing need to increase production of staple grains such as maize, rice, and wheat, whose yields are generally only 30–50 % of those in more 'advanced' agriculture. Increased production may be sought through introducing irrigation and/or improving soil and water management practices, but may not be appropriate in some ecological settings. Concerns are growing about the impact on groundwater from increasing consumptive water-use, salinity and nutrient and/or pesticide leaching.

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PRIORITY ACTIONS

- **more detailed investigation and long-term monitoring of groundwater systems are needed to establish their present resource status and flow dynamics, and to confirm current trends in storage and quality changes**
- **systematic effort needs to be put into refining operational practice for adaptive water-resource management, and especially into the promotion of conjunctive use of groundwater and surface water, rather than treating them as separate stocks**
- **detailed research (in a variety of topographic and hydrogeologic settings) is required into the response of groundwater recharge to variation of rainfall intensity, land-temperature increase and land-use change, so as to raise understanding to a level comparable to that achieved for surface-water resources**
- **improved large-scale temporal and spatial numerical modelling of ground-water systems (constrained with better field-data) is needed to advance understanding of how such systems are likely to respond to the pressures created by major land-use and accelerated climate change**

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