Groundwater and climate change

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As the world's largest distributed store of freshwater, groundwater plays a central role in sustaining ecosystems and enabling human adaptation to climate variability and change. The strategic importance of groundwater to global water and food security will likely intensify under climate change as more frequent and intense climate extremes (droughts, floods) increase variability in precipitation, soil moisture and surface water. Here we critically review recent research assessing climate impacts on groundwater through natural and human-induced processes as well as groundwater-driven feedbacks on the climate system. Further, we examine opportunities and challenges of using and sustaining groundwater resources in climate adaptation strategies, and highlight the lack of

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groundwater observations that limits current understanding of the dynamic relationship between groundwater and climate.

Groundwater is a near ubiquitous source of generally high quality freshwater. These characteristics promote its widespread development which can be scaled and localised to demand obviating the need for substantial infrastructure[1]. Globally, groundwater is the source of one third of all freshwater withdrawals supplying an estimated 36%, 42% and 27% of the water used for domestic, agricultural and industrial purposes, respectively[2]. In many environments, natural groundwater discharges sustain baseflow to rivers, lakes and wetlands during periods of low or no rainfall. Despite these vital contributions to human welfare and aquatic ecosystems, a paucity of studies of the relationship between climate and groundwater severely restricted the ability of the Intergovernmental Panel on Climate Change (IPCC) to assess interactions between groundwater and climate change in both its third[3] and fourth[4] assessment reports. There has since been a dramatic rise in published research[5-8] applying local- to global-scale modelling as well as ground-based and satellite monitoring that has considerably enhanced understanding of interactions between groundwater and climate. We build upon an earlier broad-based overview[8] and examine substantial recent advances that include emerging knowledge of direct and indirect (through groundwater use) impacts of climate forcing including climate extremes on groundwater resources as well as feedbacks between groundwater and climate such as the contribution of groundwater depletion to global sea level rise. Further, we identify critical gaps in our understanding of interactions between groundwater and climate.

Influence of climate variability and change on groundwater systems

Palaeohydrological evidence. Long-term responses of groundwater to climate forcing, largely independent of human activity, can be detected from palaeohydrological evidence from regional aquifer systems in semi-arid and arid parts of the world (Fig. 1). Much of the groundwater flowing in large sedimentary aquifers of central USA (High Plains Aquifer), Australia (Great Artesian Basin), Southern Africa (Kalahari Sands) and North Africa (Nubian Sandstone Aquifer System) was recharged by precipitation thousands of years ago[10-13]. As evaporation and plant transpiration consume soil moisture but leave chloride behind, substantial accumulations of chloride in unsaturated soil profiles within these basins indicate that little (≤ 5 mm yr^{-1}) or no recharge has since taken place across much of these basins[14]. Stable isotopes of oxygen and hydrogen together with noble gas concentrations suggest that recharge occurred under cooler climates (≥ 5°C cooler) before and occasionally during Late-Pleistocene glaciation with further local additions during the Early Holocene. Groundwater recharged during cooler, wetter climates of the Late Pleistocene and Early Holocene (≥ 5 ka B.P.) is commonly referred to as 'fossil groundwater'. As current groundwater recharge rates are responsible for at most a tiny fraction of total groundwater storage, fossil aquifers are storage dominated rather than recharge flux dominated[15]. As such, their lifespan is determined by the rate of groundwater abstraction relative to exploitable storage. In these systems, robust estimates of groundwater storage estimates and accurate records of groundwater withdrawals are of critical importance. Although fossil aquifers provide a reliable source of groundwater that is resilient to current climate variability, this non-renewable groundwater exploitation is unsustainable and is mined similar to oil[16].

Direct impacts. Current, natural replenishment of groundwater occurs from both diffuse rain-fed recharge and focused recharge via leakage from surface waters (i.e. ephemeral streams, wetlands or lakes) and is highly dependent upon prevailing climate as well as land cover and underlying geology. Climate and land cover largely determine precipitation (P) and evapotranspiration (ET) whereas the underlying soil and geology (Fig. 1) dictate whether a water surplus (P-ET) can be transmitted and stored in the subsurface. Modelled estimates of diffuse recharge globally[17,18] range from 13,000 to 15,000 km^3 $year^{-1}$, equivalent to ~30% of the world's renewable freshwater resources[19] or a mean per capita groundwater recharge of 2,100 to 2,500 m^3 $year^{-1}$. These estimates represent potential recharge fluxes as they are based on a water surplus rather than measured contributions to aquifers. Further, these modelled global recharge fluxes do not include focused recharge which, in semi-arid environments, can be substantial[14,20].

Spatial variability in modelled recharge is related primarily to the distribution of global precipitation[17,18]. Over time, recharge is strongly influenced by climate variability including climate extremes (i.e. droughts and floods) that often relate to modes of climate variability such as El Niño Southern Oscillation (ENSO) at multiyear timescales and Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO) and others at longer timescales[21,22]. During the recent multi-annual Millennium Drought in Australia, groundwater storage in the Murray-Darling Basin declined substantially and continuously by ~100 ± 35 km^3 from 2000 to 2007 in response to a sharp reduction in recharge[23]. In tropical Africa, heavy rainfall has been found to contribute disproportionately to recharge observed in borehole hydrographs[21,24]. Recharge in semi-arid environments is often restricted to statistically extreme (heavy) rainfall[17,25] that commonly generates focused recharge beneath ephemeral surface water bodies[20,21,26]. Recharge from heavy rainfall events is also associated with microbial contamination of shallow groundwater-fed water supplies and outbreaks of diarrhoeal diseases in both low and high-income countries[27]. Wetter conditions do not, however, always produce more groundwater recharge. Incidences of greater (x 2.5) winter precipitation in the SW USA during ENSO years, give rise to enhanced evapotranspiration from desert blooms that largely or entirely consume the water surplus[28].

At high latitudes and elevations, global warming changes the spatial and temporal distribution of snow and ice. Warming results in lower snow accumulation and earlier snowmelt as well as more winter precipitation falling as rain and an increased frequency of rain-on-snow events. The aggregate impact of these effects on recharge is not well resolved but preliminary evidence[29,30] indicates that changes in snowmelt regimes tend to reduce the seasonal duration and magnitude of recharge. Aquifers in mountain valleys exhibit shifts in the timing and magnitude of: (1) peak groundwater levels due to an earlier spring melt, and (2) low groundwater levels associated with longer and lower baseflow periods[31] (Fig. 2). Summer low flows in streams may be exacerbated by declining groundwater levels so that streamflow becomes inadequate to meet domestic and agricultural water requirements and to maintain ecological functions such as in-stream habitats for fish and other aquatic species[31]. The impacts of receding alpine glaciers on groundwater systems are also not well understood yet the long-term loss of glacial storage is estimated to similarly reduce summer baseflow[32]. In glaciated watersheds of the Himalayas, the impacts of large reductions in glacial mass and increased evaporation on groundwater recharge are projected to be offset by a rise in precipitation[33]. In permafrost regions where recharge is currently ignored in global analyses[17], coupling between surface water and groundwater systems may be particularly enhanced by warming[34]. In areas of seasonal or perennial ground frost, increased recharge is expected even though the absolute snow volume decreases[35].

Human and indirect climate impacts. Linkages between climate and groundwater in the modern era are complicated by Land-Use Change (LUC) that includes most pervasively the expansion of rain-fed and irrigated agriculture. Managed agro-ecosystems do not respond to changes in precipitation in the same manner as natural ecosystems. Indeed, LUC may exert a stronger influence on terrestrial hydrology than climate change. Under multi-decadal droughts in the West African Sahel during the latter half of the 20th century, groundwater recharge and storage rose rather than declined due to a coincidental LUC from savannah to cropland that increased surface runoff through soil crusting and focused recharge via ephemeral ponds[36]. Much earlier in the 20th century, LUC from natural ecosystems to rain-fed cropland in SE Australia and SW USA similarly increased groundwater storage through increased recharge but also degraded groundwater quality through the mobilisation of salinity accumulated in unsaturated soil profiles[14]. In both regions, recharge rates under cropland increased by one to two orders of magnitude[37-39] compared with native perennial vegetation.

Humans have also exerted large-scale impacts on the terrestrial water system through irrigation (Fig. 2). In 2000, irrigation accounted for ~70% of global freshwater withdrawals and ~90% of consumptive water use[2]. This large-scale redistribution of freshwater from rivers, lakes and groundwater to arable land (Fig. 2) has led to: (1) groundwater depletion in regions with primarily groundwater-fed irrigation; (2) groundwater accumulation as a result of recharge from return flows from surface-water fed irrigation; and (3) changes in surface-energy budgets associated with enhanced soil moisture from irrigation. Irrigation has depleted groundwater storage in several semi-arid and arid environments including the North China Plain[40], NW India[41], US High Plains[42,43] but also in humid environments of Brazil[44] and Bangladesh[45] (Fig. 1) where abstraction is especially intense. During a recent (2006 to 2009) drought in the California Central Valley (Fig. 1), large-scale groundwater depletion occurred when the source of irrigation water shifted from surface water to predominantly groundwater. GRACE (Gravity Recovery and Climate Experiment) satellite data and ground-based observations revealed that groundwater storage declined by between 24 and 31 km^3, a volume that is equivalent to the storage capacity of Lake Mead, the largest surface reservoir in the USA[46,47]. Thus indirect effects of climate on groundwater through changes in irrigation demand and sources can be greater than direct impacts of climate on recharge. Global-scale modelling[2] highlights areas of recent (1998 to 2002) groundwater accumulation through irrigation return flows from surface-water fed irrigation in the Nile Basin of Egypt, Tigris-Euphrates basin of Iraq, Syria and Turkey, the lower Indus basin in Pakistan, and southeastern China (Fig. 3). In parts of the California Central Valley, surface water irrigation since the 1960s has increased groundwater recharge by a factor of ~7 replenishing previously depleted aquifers and raising groundwater levels by up to 100 m[48]. Increased recharge may also serve not only to degrade groundwater quality through the mobilisation of salinity in soil profiles (discussed above) but also to flush natural contaminants such as arsenic from groundwater systems[49,50].

Future climate impacts on groundwater systems. As irrigation dominates current groundwater use and depletion, the effects of future climate variability and change on groundwater may be greatest through indirect impacts on irrigation water demand. Substantial uncertainty persists in climate change impacts on mean precipitation from General Circulation Models (GCMs)[51] but there is much greater consensus on changes in precipitation and temperature extremes, which are projected to increase with intensification of the global hydrological system[52,53]. Longer droughts may be interspersed with more frequent and intense rainfall events. These changes in climate may affect groundwater initially and primarily through changes in irrigation demand, in addition to changes in recharge and discharge. A global analysis of climate change impacts on irrigation demand suggests that two thirds of the irrigated area in 1995 will be subjected to increased water requirements for irrigation by 2070(54). Projected increases in irrigation demand in southern Europe will serve to stress further limited groundwater resources[55]. Persistent droughts projected in the California Central Valley over the latter half of the 21st century may trigger a shift from predominantly surface water to groundwater supply for agriculture[56]. Increased groundwater abstraction combined with reduced surface water flows associated with intermittent droughts during the first half of the 21st century may, however, induce secondary effects (e.g. land subsidence) that severely constrain this future adaptation strategy.

Projections of the direct impacts of climate change on groundwater systems are highly uncertain. The dominant source of uncertainty lies in climate projections derived from GCMs which typically translate the same emissions scenarios into very different climate scenarios, particularly for precipitation[51]. Nevertheless, GCM projections of global precipitation for the 21st century broadly indicate a ‘rich get richer’ pattern in which regions of moisture convergence (divergence) are expected to experience increased (decreased) precipitation[52,57]. At the global scale, there are no published studies applying a large ensemble of GCMs and greenhouse-gas emissions scenarios to generate recharge projections. Global simulations employing output from two climate models (ECHAM4, HadCM3) under two emissions scenarios (A2, B2) project: (1) decreases in potential groundwater recharge of more than 70% by the 2050s in NE Brazil, SW Africa and along the southern rim of the Mediterranean Sea; and (2) increases in potential recharge of more than

30% in the Sahel, Middle East, northern China, Siberia and the western USA[17]. Baseline recharge rates in many of these areas are, however, very low so that small changes in projected recharge can result in large percentage changes. For most of the areas with high population densities and high sensitivity to groundwater recharge reductions, model results indicated that groundwater recharge is unlikely to decrease by more than 10% until the 2050s[19].

Groundwater recharge projections relate closely to projected changes in precipitation. Regional simulations employing 16 GCMs in Australia project potential recharge decreases in the west, central and south, and increases in the north based on the ensemble median[57]. In Europe, potential recharge projections derived from an ensemble of four GCMs under the A1FI emissions scenario demonstrate strong latitudinal dependence on the direction of the climate change signal[58]. Substantial reductions in potential groundwater recharge are projected in southern Europe (Spain and northern Italy) whereas increases are consistently projected in northern Europe (Denmark, southern England, northern France). Current uncertainty in climate change impacts on recharge derives not only from the substantial uncertainty in GCM projections of precipitation but also from the cascade of uncertainty associated with the downscaling of GCM projections and employed hydrological models[59]. For a chalk aquifer in England, for example, application of an ensemble of 13 GCMs resulted in projected changes in groundwater recharge for the 2080s of between -26% and +31%[60]. In southern British Columbia, recharge projections for the 2080s range from -10 % to +23 % relative to historical recharge[61]. At three Australian sites, the choice of GCMs was found to be the greatest source of uncertainty in future recharge projections followed by that of downscaling and, in turn, the applied hydrological model amounting to 53, 44 and

24% of historical recharge, respectively[62]. Uncertainty from downscaling can be greater than uncertainty due to the choice of applied emissions scenarios[63,64].

Current projections of groundwater recharge under climate change commonly do not consider the intensification of precipitation and CO_2-physiological forcing. Although precipitation intensity is of critical importance to recharge, historical daily rainfall distributions are typically used to downscale monthly rainfall projections to a daily timestep. Evidence from the tropics[65] where the intensification of precipitation is expected to be especially strong, reveals that failure to consider changes in daily rainfall distributions can systemically underestimate future recharge. Transformation of the rainfall distribution to account for changes in rainfall intensity reversed a projected 55% decline in potential recharge to a 53% increase. Recent multi-model simulations that account for precipitation intensification[66] represent a critical advance in assessing climate change impacts on groundwater recharge and terrestrial water balances. Under higher atmospheric CO_2 concentrations, terrestrial plants open their stomata less; this response is projected to reduce evapotranspiration and increase continental runoff[67]. Recent analyses in Australia[68] highlight that: (1) greater plant growth (i.e. greater leaf area) can offset reductions in evapotranspiration through stomatal closure; (2) reduced leaf area due to unfavorable climate conditions can result in an increase of groundwater recharge even with slightly decreased rainfall; and (3) changes in rainfall intensity can have a greater impact on recharge fluxes than rising atmospheric CO_2 concentrations.

Groundwater Impacts on the Climate System

Groundwater-fed irrigation and soil moisture. Groundwater primarily influences climate through contributions to soil moisture. Irrigation can transform areas from moisture-limited to energy-limited evapotranspiration thereby influencing water and energy budgets. A modeling study[69] estimated that during the growing season and averaged over the continental United States, irrigation increases evapotranspiration by 4%. Simulations show that rising groundwater-fed irrigation in the High Plains (Fig. 1) over the 20th century increased downwind precipitation by ≤15 to 30 % in July[70] with associated increases in groundwater storage and streamflow observed from August to September[71]. Irrigation in California's Central Valley has strengthened the southwestern U.S. monsoon, increasing precipitation by 15% and discharge of the Colorado River by 30%[72]. Similar impacts of groundwater-fed irrigation on evapotranspiration and downwind precipitation have been demonstrated in the Indian monsoon region using a regional climate model[73].

Groundwater in land-surface models. Land surface models (LSMs), embedded in GCMs, have neglected hydrological processes below the root zone such as lateral groundwater flow as these have been assumed to be disconnected from the atmosphere. LSMs were subsequently retrofitted with a simplified formulation of unconfined groundwater storage changes[74]. There have also been attempts to better represent subsurface processes in LSMs[75] or to couple more complete groundwater models to LSMs[76]. These efforts led to the discovery of a critical zone of water table depths from 2 to 7 m where groundwater exerts the most influence on land-energy fluxes[77]. Coupling of an integrated hydrological model to mesoscale atmospheric models[78] revealed clear connections between water-table depth and development of the atmospheric boundary layer[79]. Representing groundwater flow in atmospheric models at larger scales and longer time frames affects land surface moisture states that feed back into regional climate where water tables are relatively shallow[80]. Without a prognostic groundwater reservoir and explicit groundwater-surface water exchanges in LSMs, we remain unable to represent the integrated response of the water cycle to human perturbations and climate change. One key groundwater process missing from LSMs is lateral groundwater flow. This flow occurs at multiple spatial scales[81] but is fundamentally important at hillslope (or small model grid) scales in a humid climate or at basin scales in semi-arid and arid climates with regional aquifers where discharges can be remote from sources of recharge[82]. Lateral groundwater flow supports persistently wetter river valleys in humid climates and regional wetlands and oases in arid climates[80] affecting land surface moisture states and ET fluxes. Groundwater also acts as an important store and vehicle for carbon though studies accounting for groundwater interactions and feedbacks in the global carbon budget are still in their infancy[83].

Groundwater and sea-level rise. Coastal aquifers form the interface between the oceanic and terrestrial hydrological systems and provide a source of water for the more than one billion people in coastal regions[84]. Global sea-level rise (SLR) of 1.8 mm yr^{-1} over the second half of the twentieth century[85] is expected to have induced fresh-saline water interfaces to move inland. The extent of seawater intrusion into coastal aquifers depends on a variety of factors including coastal topography, recharge, and groundwater abstraction from coastal aquifers[86,87]. Analytical models suggest that the impact of SLR on seawater intrusion is negligible compared to that of groundwater abstraction[87]. The impacts of seawater intrusion have been observed most prominently in association with intensive groundwater abstraction around high population densities (e.g. Bangkok, Jakarta, Gaza)[88,89]. Coastal aquifers under very low hydraulic gradients such as the Asian mega-deltas are theoretically sensitive to SLR but, in practice, are expected in coming decades to be more severely impacted by saltwater inundation from storm surges than SLR[87].

Groundwater depletion contributes to SLR through a net transfer of freshwater from long-term terrestrial groundwater storage to active circulation near the earth's surface and its eventual transfer to oceanic stores. The contribution of groundwater depletion to SLR has, however, been a subject of debate. In the IPCC AR4[90], the contribution of non-frozen terrestrial waters including groundwater depletion to sea-level variation was not specified due to its perceived uncertainty. Recently, there has been a series of studies estimating the contribution of groundwater depletion to SLR[18,91-93]. Current estimates of global groundwater depletion derived from flux-based (year 2000) and volume-based (period: 2001-2008) methods are summarised in Table 1. Global groundwater depletion (204 ± 30 km^3 $year^{-1}$) estimated by the flux-based method[91], is based on the difference between grid-based simulated groundwater recharge and net abstraction (i.e. groundwater withdrawals minus return flows). This approach overestimates depletion as it does not account for increased capture due to decreased groundwater discharge and long-distance surface-water transfers. The volume-based method[92] combines evidence of groundwater storage changes for the US and another five aquifer systems (Indo-Gangetic Plain, North China Plain, Saudi Arabia, Nubian Sandstone and North West Sahara) (Fig. 1) and then extrapolates groundwater depletion elsewhere using the average ratio of depletion to abstraction observed in the US. This approach produces a lower global estimate of groundwater depletion (145 ± 39 km^3 $year^{-1}$) than the flux-based approach. Both methods reveal that groundwater depletion is most pronounced in Asia (China, India) and North America (Table 1). The different estimates of global groundwater depletion produce variable estimates of its current contribution to SLR (34% or 0.57 ± 0.09 mm $year^{-1}$ versus 23% or 0.4 ± 0.1 mm $year^{-1}$). Direct observations of groundwater depletion continue to be hampered by a dearth of ground-based observations that not only limits understanding of localised groundwater storage changes but also our ability to constrain evidence from GRACE satellite observations at larger scales (≥ 150 000 km^2).

A look forward

Groundwater can enhance the resilience of domestic, agricultural and industrial uses of freshwater to climate variability and change. As the only perennial source of freshwater in many regions, groundwater is of vital importance to the water security of many communities including most critically rural dwellers in low-income countries. Groundwater-fed irrigation provides a buffer against climate extremes and is consequently essential to global food security. Further, it serves to alleviate poverty in low-income countries by reducing crop failure and increasing yields[94]. The value of groundwater is expected to increase in coming decades as temporal variabilities in precipitation, soil moisture and surface water are projected to increase under more frequent and intense climate extremes associated with climate change[53]. Indeed, in light of the resilience of groundwater resources to hydrological extremes, groundwater can play a strategic role in sustaining drinking water supplies under emergency conditions[95].

As detailed above, substantial uncertainty remains in the projected impacts of climate change on diffuse groundwater recharge that is associated with climate projections[96] and terrestrial responses to changing precipitation and land cover. More certain are rises in groundwater abstraction in absolute terms and as a proportion of total water withdrawals, that threaten to overexploit groundwater resources. This risk is particularly acute in semi-arid regions where projected increases in the frequency and intensity of droughts, combined with rising populations and standards of living as well as the projected expansion of irrigated land, will intensify groundwater demand. To sustain groundwater use under these conditions will require careful aquifer management[97] that: (1) is informed by integrated models able to consider the range of interactions between groundwater, climate and human activity (summarised in Fig. 2); and (2) exploits opportunities for enhanced groundwater recharge associated with less frequent but heavier rainfall events and changing meltwater regimes.

Comprehensive management approaches to water resources that integrate groundwater and surface water may greatly reduce human vulnerability to climate extremes and change, and promote global water and food security. Conjunctive uses of groundwater and surface water that employ surface water for irrigation and water supply during wet periods and groundwater during drought[48], are likely to prove essential. Recognition of current uncertainty in water resource projections and the longer residence time (decadal to multigenerational) of freshwater in groundwater systems will be critical in setting sustainability goals[97]. Managed aquifer recharge wherein excess surface water, desalinated water, and treated wastewater are stored in depleted aquifers could also supplement groundwater storage for use during droughts[43,98]. Indeed, the use of aquifers as natural storage reservoirs avoids many of the problems of evaporative losses and ecosystem impacts associated with large, constructed surface water reservoirs. In South Asia for example, intensive groundwater abstraction for dry season irrigation has induced greater recharge in areas with permeable soils by increasing available groundwater storage during the subsequent monsoon[99]. In northern Europe, capture of projected increases in groundwater recharge during winter may help to sustain anticipated increases in summer demand[58]. Explicit representation in GCMs of groundwater storage, its interactions with surface water stores, and anthropogenic perturbations such as large-scale groundwater-fed irrigation is required to advance understanding of both the influence of groundwater on climate and the impact of climate change on global freshwater resources.

A fundamental impediment to employing adaptation strategies discussed above is the lack of groundwater observations to inform them. Since 2002, GRACE satellite observations have provided valuable information on recent groundwater storage changes at basin scales but ground-based data are essential to constrain satellite observations and to inform local groundwater responses to climate and abstraction. The Global Groundwater Monitoring Network (GGMN), initiated in 2007 by the UNESCO-IHP International Groundwater Resources Assessment Centre (IGRAC) to facilitate the sharing of groundwater information globally, has begun collating datasets from publicly accessible sources and via participatory processes. The first global maps of groundwater resources were compiled in 2004(9) and groundwater has recently been incorporated into the Global Earth Observation System of Systems (GEOSS). Nevertheless, the availability of groundwater data (e.g. groundwater levels and withdrawals) remains limited. As a result, the ability to evaluate fully the responses of groundwater to climate variability and change, to estimate directly groundwater replenishment, and to constrain models and satellite observations, is severely impaired. There is, for example, a profound lack of knowledge regarding the quantity of groundwater storage in most aquifers that may be sustainably used. The equivalent depth of groundwater storage, determined primarily by geology, can vary substantially from regional sedimentary aquifers (>50 m) to small, discontinuous aquifers in deeply weathered crystalline rock (<1 m) that underlie 40% of sub-Saharan Africa[100]. An expansion of groundwater monitoring together with increased contributions of data to the GGMN are necessary to improve access to groundwater data globally and promote the inclusion of groundwater in the assessment and management of freshwater resources under climate change.

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Table 1. Flux-based and volume-based estimates of global and continental-scale groundwater depletion (km^3 year^{-1}) and their contributions to global sea-level rise (mm year^{-1}).

Region	**flux-based method (ref. 92)***		**volume-based method (ref. 93)^**	
	gw depletion	sea-level rise	gw depletion	sea-level rise
World	204 ± 30	0.57 ± 0.09	145 ± 39	0.40 ± 0.11
Asia	150 ± 25	0.42 ± 0.07	111 ± 30	0.31 ± 0.08
Africa	5.0 ± 1.5	0.014 ± 0.004	5.5 ± 1.5	0.015 ± 0.004
N. America	40 ± 10	0.11 ± 0.03	26 ± 7	0.07 ± 0.02
S. America	1.5 ± 0.5	0.0042 ± 0.0014	0.9 ± 0.5	0.002 ± 0.001
Australia	0.5 ± 0.2	0.0014 ± 0.0006	0.4 ± 0.2	0.001 ± 0.0005
Europe	7 ± 2	0.02 ± 0.006	1.3 ± 0.7	0.004 ± 0.002

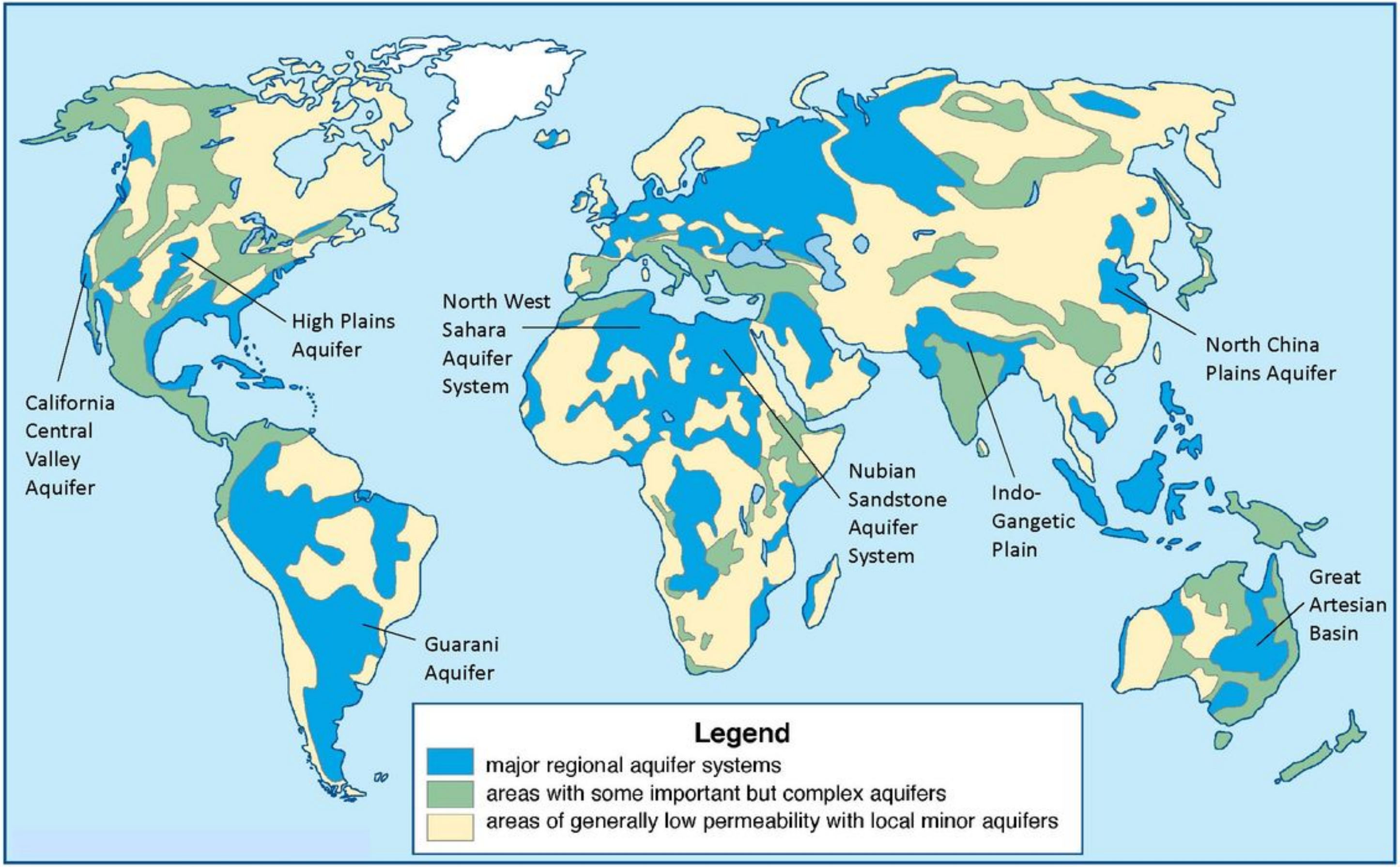
**year 2000; ^period of 2001 to 2008*

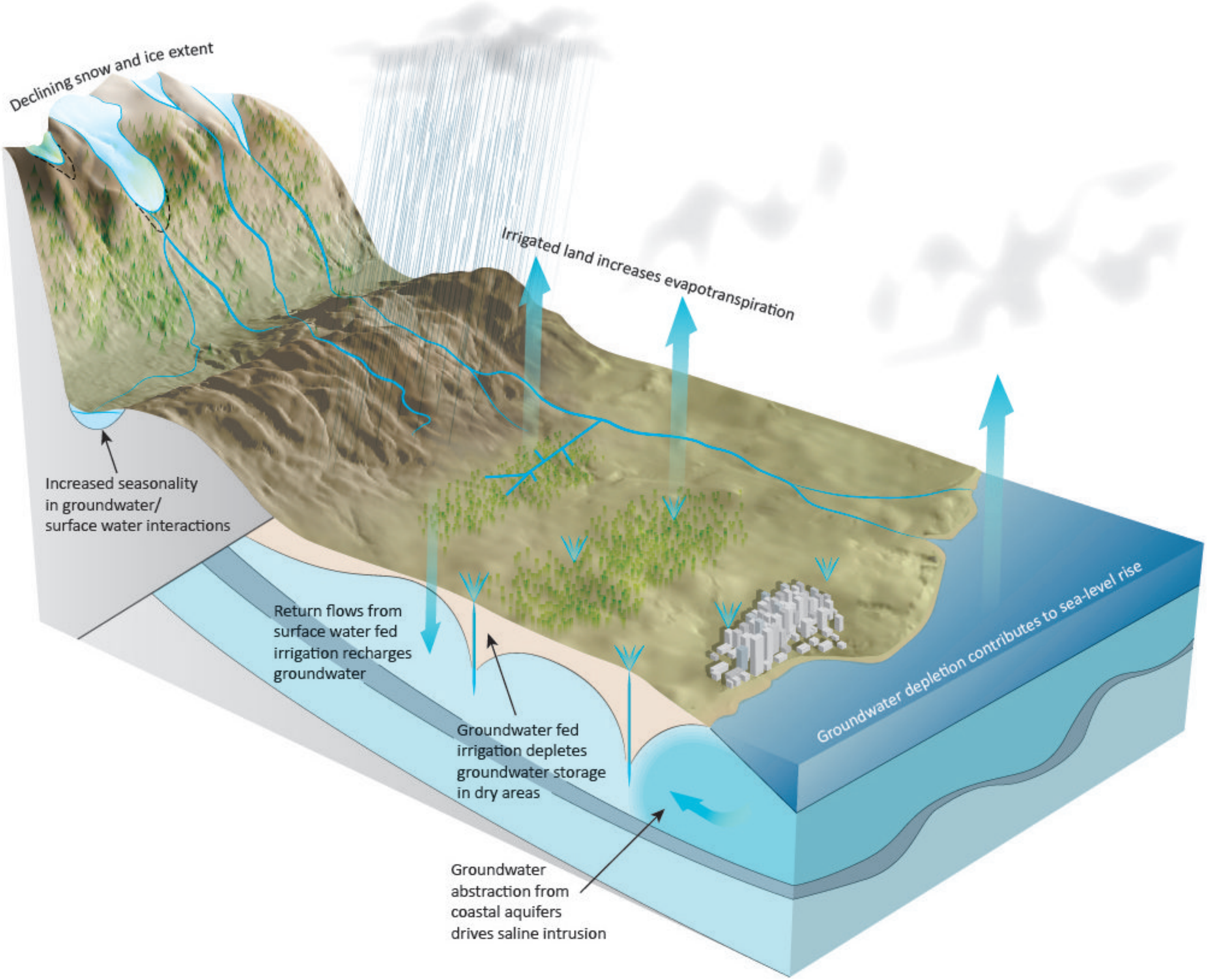
FIGURE CAPTIONS:

Figure 1. Simplified version of a global groundwater resources map[9] highlighting the locations of regional aquifers systems.

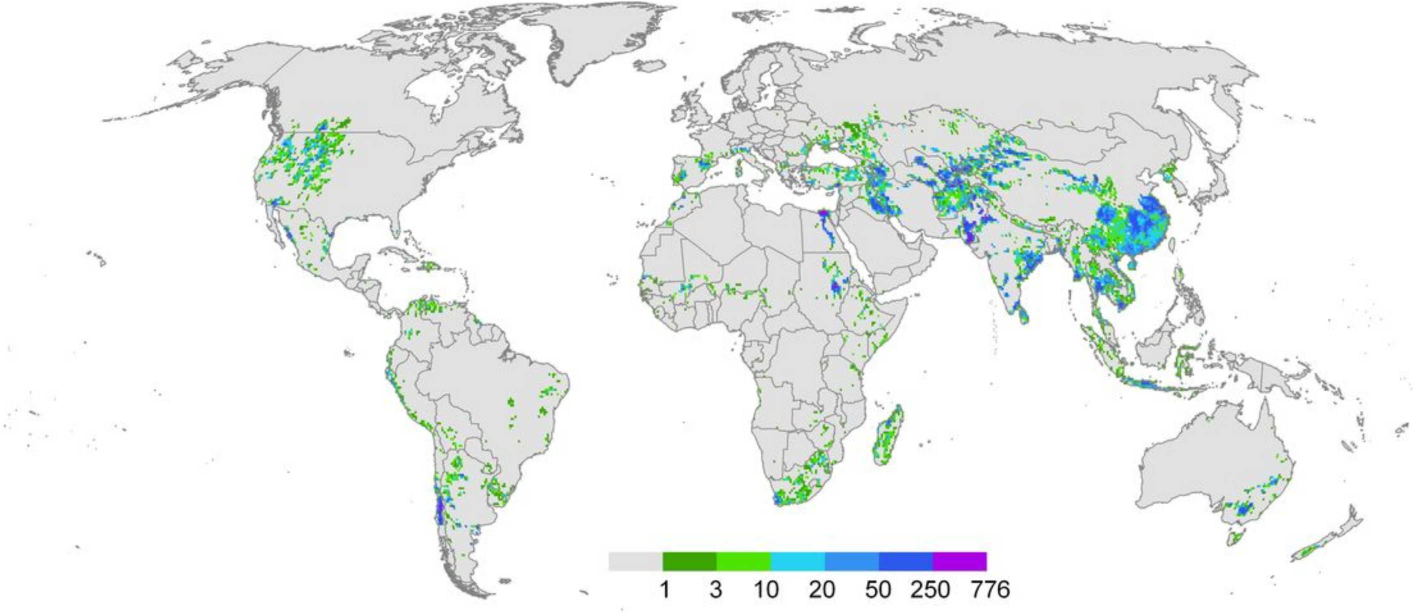
Figure 2. Conceptual representation of key interactions between groundwater and climate.

Figure 3. Global map of anthropogenic groundwater recharge rates in areas with substantial irrigation by surface water. Rates are estimated from the difference between the return flow of irrigation water to groundwater and total groundwater withdrawals (mm yr^{-1}) for the period 1998 to 2002(2). Note that in areas with predominantly groundwater-fed irrigation or significant water withdrawals for domestic and industrial purposes, no anthropogenic groundwater recharge occurs; a net abstraction of groundwater leads to groundwater depletion in regions with insufficient natural groundwater recharge.


High Plains Aquifer
California Central Valley Aquifer
North West Sahara Aquifer System
Nubian Sandstone Aquifer System
Indo-Gangetic Plain
North China Plains Aquifer
Great Artesian Basin
Guarani Aquifer
Legend
🟦 major regional aquifer systems
🟩 areas with some important but complex aquifers
🟨 areas of generally low permeability with local minor aquifers



Declining snow and ice extent
Irrigated land increases evapotranspiration
Increased seasonality in groundwater/ surface water interactions
Return flows from surface water fed irrigation recharges groundwater
Groundwater fed irrigation depletes groundwater storage in dry areas
Groundwater depletion contributes to sea-level rise
Groundwater abstraction from coastal aquifers drives saline intrusion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