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Will groundwater ease freshwater stress under climate change?

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Abstract Today, groundwater is the source of about one third of global water withdrawals and provides drinking water for a large portion of the global population. In many regions it is subject to stress with respect to both quantity and quality. Hence, it is of utmost importance to improve our knowledge about the impacts of climate change on groundwater. Climate change will affect groundwater recharge, i.e. long-term average renewable groundwater resources, via increases in mean temperature, precipitation variability and sea level, as well as via changes in mean precipitation (increasing in some areas and decreasing in others). Over many areas groundwater recharge is projected to increase in the warming world (though less than river runoff), but many semi-arid areas that suffer from water stress already may face decreased groundwater recharge. The sea level rise that is likely to occur during the 21st century might leave many flat coral islands without a reliable groundwater source. However, in coastal areas with a land surface elevation of a few metres or more, groundwater availability is more strongly impacted by changes in groundwater recharge than sea-level rise. Under climate change, reliable surface water supply is likely to decrease due to increased temporal variations of river flow that are caused by increased precipitation variability and decreased snow/ice storage. Under these circumstances, it might be beneficial to take advantage of the storage capacity of groundwater and increase groundwater withdrawals. However, this option is only sustainable where groundwater withdrawals remain well below groundwater recharge. Groundwater is not likely to ease freshwater stress in those areas where climate change is projected to decrease groundwater recharge (e.g. Northeast Brazil and the Mediterranean basin).

Key words groundwater; freshwater resources; climate change; projections; impacts; groundwater recharge

Les eaux souterraines vont-elles diminuer le stress sur les eaux douces en contexte de changement climatique?

Résumé Aujourd'hui, les eaux souterraines sont la source d'environ un tiers des prélèvements d'eau mondiaux et fournissent l'eau potable à une grande partie de la population globale. Les eaux souterraines subissent, dans de nombreuses régions, un stress en termes aussi bien quantitatifs que qualitatifs. Il est par conséquent capital d'améliorer nos connaissances concernant les impacts du changement climatique sur les eaux souterraines. Le changement climatique va affecter la recharge des nappes, i.e. les ressources moyennes en eaux souterraines renouvelables à long terme, via l'augmentation de la température moyenne, l'augmentation de la variabilité des précipitations et l'élévation du niveau de la mer, ainsi que via des changements de pluviosité moyenne (en augmentation dans certaines régions et en diminution dans d'autres). La recharge des eaux souterraines devrait augmenter dans de nombreuses régions d'un monde en cours de réchauffement (mais moins que l'écoulement en rivières), mais de nombreuses régions semi-arides qui souffrent déjà aujourd'hui de stress hydrique risquent de subir une diminution de la recharge en eaux souterraines. Une élévation du niveau de la mer, telle qu'elle est susceptible de se manifester au cours du 21ème siècle, pourrait priver de nombreuses îles coralliennes plates de ressources fiables en eaux souterraines. Cependant, dans les zones côtières de quelques mètres d'altitude ou plus, la disponibilité en eau souterraine est plus fortement impactée par les changements de recharge en eaux souterraines que par l'élévation du niveau de la mer. Sous l'influence du changement climatique, la fiabilité de l'alimentation en eaux de surface devrait diminuer en raison d'une augmentation des variations temporelles des écoulements en rivière suite à une augmentation de la variabilité des précipitations et à une diminution des stockages nivo-glaciaires. Dans de telles circonstances, il pourrait être bénéfique de tirer avantage de la capacité de stockage des nappes souterraines et d'augmenter les prélèvements d'eaux souterraines. Cependant cette option n'est durable que là où les prélèvements restent bien inférieurs à la recharge en eaux souterraines. Les eaux souterraines ne devraient pas réduire le stress sur les eaux douces dans les régions où les projections montrent que le changement climatique engendrera une diminution de la recharge en eaux souterraines (e.g. dans le Nord-est du Brésil et dans le Bassin Méditerranéen).

Mots clefs eaux souterraines; ressources en eau douce; changement climatique; projections; impacts; recharge en eaux souterraines

INTRODUCTION

Global water demands have increased 35-fold in the last 300 years and continue to grow (Jones, 1999). In the future, growth in population, wealth, industrial activity and energy consumption will

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lead to growing water scarcity over many regions. According to the model-based projections of Alcamo *et al.* (2007), the area of increasing water stress, in which the ratio of water withdrawal to long-term average annual water resources is larger than 0.4, will exceed (approx. two- to four-fold) the area of decreasing water stress until the 2050s; however, the quantitative projections strongly depend on the scenario and the climate model applied.

Water on Earth, the so-called hydrosphere, is stored in different reservoirs in the geosphere: in the atmosphere, in water bodies that primarily consist of (liquid or solid) water (oceans, lakes and rivers, snow and ice), and in wetlands, soils and groundwater bodies. Groundwater is the third largest storage, after oceans (saltwater) and the cryosphere (freshwater in snow and ice), but by far the largest available reservoir of liquid freshwater (approx. 10.5 million km^3, i.e. 0.76% of the total water on Earth; Shiklomanov & Rodda, 2003). However, there is great uncertainty in estimates of the volume of fresh groundwater, ranging from 7 million to 23 million km^3 (UN-WWAP, 2003; Vörösmarty *et al.*, 2005). For the sustainable use of a resource, however, it is not the storage but the fluxes that are relevant. In the case of groundwater, long-term average groundwater recharge determines the maximum value that human water withdrawals may reach without leading to groundwater depletion, i.e. falling groundwater tables. However, the notion of groundwater recharge should not be explicitly equated with the concept of safe yield, referring to the amount of water that can be withdrawn from an aquifer or a well without producing unacceptable negative effects (also to surface waters—wetlands, streams, sources). The complexities of the safe yield concept were discussed by Sophocleous (1998, 2002). Thus, renewable groundwater resources can be defined as being equal to long-term average groundwater recharge.

As pointed out by Dr John C. Rodda (personal communication), we are guessing rather than assessing global water resources. Surface freshwater resources (river discharges, lake levels) are not adequately monitored and hydrographic networks are shrinking worldwide. However, knowledge about the historic development and current state of groundwater resources worldwide is even more scarce when compared to surface water resources, and global-scale efforts to improve that situation have only recently begun. One such effort is the GRACE mission, where seasonal and inter-annual continental water storage changes are deduced from variations in the Earth's gravity field. However, even though the contribution of groundwater storage variations to total water storage variations can be large (Güntner *et al.*, 2007a,b), generally it cannot be deduced directly from the measurements but only by applying hydrological models. Regarding *in situ* information, poor data harmonization, incomplete and fragmentary inventories, and methodological difficulties are well recognized (UN-WWAP 2003; Vörösmarty *et al.*, 2005). Well-log, groundwater discharge/recharge, and aquifer property data for global applications are only beginning to be synthesized (UNESCO-IHP, 2004; Vörösmarty *et al.*, 2005). A concerted effort to collect groundwater-related information on e.g. groundwater tables, groundwater bodies, groundwater recharge, or the occurrence of karst aquifers at the global scale, would improve the basis for assessing the future of groundwater. This information needs to be made available to scientists and policy makers, e.g. by the International Groundwater Resources Assessment Centre (IGRAC).

Groundwater is an attractive source of freshwater because it allows withdrawals even during dry seasons when rivers carry little or no water, and is often less polluted than surface water. Today, groundwater is the source of about one third of global water withdrawals (Vörösmarty *et al.*, 2005). Estimates of the number of people who depend on groundwater supplies for drinking range from 1.5 to 3 billion. Global groundwater abstraction grew from about 100 km^3/year in 1950 to about 1000 km^3/year today, largely concentrated in agriculture (approx. 90%), particularly in Asia (Shah *et al.*, 2007). Groundwater use, in relative terms, has increased in recent decades as compared to surface water use. On the one hand, groundwater use is technically more involved and more expensive than surface water use, except for large-scale development of surface water (e.g. large dams); on the other hand, it is more reliable and safer. In some areas, such as India and Australia, surface water may no longer be available.

Groundwater is subject to stress with respect to both quantity and quality. Many aquifers, in particular in semi-arid and arid regions, suffer from overexploitation. Withdrawals exceed recharge rates, causing environmental problems, increasing pumping costs, and the loss of the resource for future generations. Non-renewable resources are locked in deep aquifers with insignificantly small, if any, current recharge, and are mined when abstracted; hence, future generations may be deprived of these resources (Margat *et al.*, 2006). This raises sustainability concerns. In the arid Middle East and North Africa, this water is mainly used for irrigation. For example, Saudi Arabia meets nearly all its irrigation requirements through non-renewable groundwater. The Great Man-Made River Project in Libya transports over 2 km^3/year of non-renewable groundwater through a 1600-km-long pipeline to huge coastal storage reservoirs that support 135 000 ha of irrigable cropland, one third of the country's total (UN-WWAP, 2003). Groundwater pollution has become a burning problem, since, globally, most of the wastewater (domestic and industrial) is not treated, so that pathogens, nutrients, heavy metals and organic micropollutants enter into the water cycle. In some coastal areas, overpumping has led to saltwater intrusion.

Groundwater resources are impacted by changes in land use and land cover. Urbanization leads to lower long-term average groundwater recharge and thus less renewable groundwater resources. While reforestation decreases total runoff, its impact on groundwater recharge is site-dependent. Groundwater use is not only constrained by groundwater recharge but also by hydrogeological characteristics. According to the recently developed map (cf. UNESCO-IHP, 2004), *Groundwater Resources of the World* (www.whymap.org), about 30% of the area of the continents (excluding the Antarctic) is underlain by relatively homogeneous aquifers and 19% is endowed with groundwater in geologically complex regions. Half of the continental areas contain generally minor occurrences of groundwater that are restricted to near-surface unconsolidated sediments.

In the following, we first synthesize the current knowledge of the impacts of climate change on freshwater resources in general. We then focus on the impacts on groundwater and, finally, discuss where and under what circumstances groundwater may ease freshwater stress under climate change.

CLIMATE CHANGE—OBSERVATIONS AND PROJECTIONS

Temperature

As noted by the IPCC (2007), warming of the global climate system has been unequivocal. This is now evident from observations of increases in air temperatures in all regions. The IPCC Fourth Assessment Report (2007) conveys the statement that most of the observed increase in global mean air temperature since the mid-20th century is very likely due to the rise in atmospheric greenhouse gas concentrations, caused by increasing anthropogenic emissions of such gases as carbon dioxide, methane, nitrous oxide, and by land-use changes (such as deforestation). The updated 100-year linear trend (1906–2005) shows a 0.74°C global mean temperature increase, while the linear warming trend over the last 50 years (0.65°C) is nearly twice as strong as that for the last 100 years (IPCC, 2007). Thirteen of the 14 globally warmest calendar years in the global instrumental observation record, available since 1850, occurred during the last 14 years (1995–2008). Each of the years 2001–2008 belongs to the ten warmest years on record. Even if the year with the highest global mean annual temperature is still 1998 (related to a strong El Niño phase), local and regional records have been established more recently in the 2000s. It was shown by Kundzewicz *et al.* (2008b) that, in 2006–2007, the highest mean average temperature over 12 consecutive months, since the beginning of records, was reached on a number of scales, from local to hemispheric.

For the next two decades a warming of about 0.2°C per decade is projected for a range of emission scenarios from the IPCC *Special Report on Emissions Scenarios* (SRES, Nakićenović & Swart, 2000); for a brief review of scenarios, see IPCC (2007). Even if the concentrations of all greenhouse gases and aerosols had been kept constant at the year 2000 levels, a further warming of about 0.1°C per decade would be expected. According to the IPCC, the likely range of global mean temperature for 2100 without climate policy is from 1.1 to 6.4°C. All climate models project warming everywhere and predict that hot extremes and heat waves will become more frequent in the future, but the magnitude of temperature change varies among models (IPCC, 2007).

Precipitation

Global temperature changes are accompanied by changes in other climatic variables. Patterns of precipitation change are more spatially and temporally variable than temperature change. Based on sparse observation records, there is no statistically significant long-term trend in the time series of global precipitation in the period 1900–2005 (Trenberth *et al.*, 2007). Global mean changes in terrestrial precipitation volumes were not uniform in time, with an overall increase until the 1950s, peaks in the 1950s and then in the 1970s, a decline from the 1970s until the early 1990s, and a recovery afterwards. As summarized in Trenberth *et al.* (2007), long-term precipitation trends have been found in many large regions where sufficient data exist. Total precipitation depth has generally increased over land in most higher-latitude areas of the Northern Hemisphere (north of 30°N), and in parts of the wet tropics. Precipitation decreased in the region between 30°N and 10°S, especially after 1977, as well as in South Africa.

As regards future projections of precipitation, different climate models do not agree well (even as to the direction of change) for most areas of the globe (Fig. 1). In high latitudes and parts of the tropics, climate models are consistent in projecting precipitation increases, while in some subtropical and lower mid-latitude regions, they are consistent in projecting precipitation decreases. However, it should be noted that even the agreement of a large number of models is not necessarily proof of the results' credibility. Between the areas of robust model-projected increase and decrease, there is more uncertainty in projections, and predicted magnitudes of change differ very strongly. For precipitation changes until the end of the 21st century, the multi-model ensemble mean change exceeds the inter-model standard deviation only at high latitudes, i.e. uncertainty is lower there than in other latitudes (IPCC, 2007).

With respect to increasing precipitation variability, more intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Precipitation intensity increased over most land areas, but particularly at middle and high latitudes where mean precipitation also increased (Tebaldi *et al.*, 2006; Meehl *et al.*, 2007). Climate models project that the frequency of heavy precipitation and the maximum number of consecutive days without precipitation will increase in the future, even for some regions where the mean precipitation is projected to decrease (Fig. 2). In Fig. 2, precipitation intensity is defined as the annual total precipitation divided by the number of wet days (mm d^{-1}), and dry days are defined as the annual maximum number of consecutive dry days. Three SRES scenarios considered are: low (SRES B1), middle (SRES A1B) and high (SRES A2). The higher the greenhouse gas emissions, the stronger is the increase in precipitation variability (Fig. 2).

Each model's time series used for development of Fig. 2 was centred on its 1980–1999 average and normalised (rescaled) by its standard deviation computed (after de-trending) over the period 1960–2099. The models were then aggregated into an ensemble average, both at the global and at the grid-box level. Thus, changes are given in units of standard deviations.

Sea-level rise

Globally-averaged sea level has risen by 17 cm (12–22 cm) over the 20th century, at a rate of 1.8 mm/year (1.3–2.3) from 1961 to 2003 and about 3.1 mm/year (2.4–3.8) from 1993 to 2003 (IPCC, 2007). Most of the sea-level rise in 1993–2003 has been caused by thermal expansion (1.6 mm/year); less than half (0.77 mm/year) stems from melting glaciers and ice caps, and about a quarter (0.42 mm/year) from Greenland and Antarctic ice sheets (the contribution of the latter is highly uncertain—the uncertainty range exceeds the mean change by the factor of three; IPCC, 2007). Over the 21st century, sea level is projected to rise faster, so that the range of growth, over all emissions scenarios, for the time horizon 2090–2099, in comparison to 1980–1999, is 18–59 cm, (under the assumption of no rapid changes in ice flow). The upper values of the range have

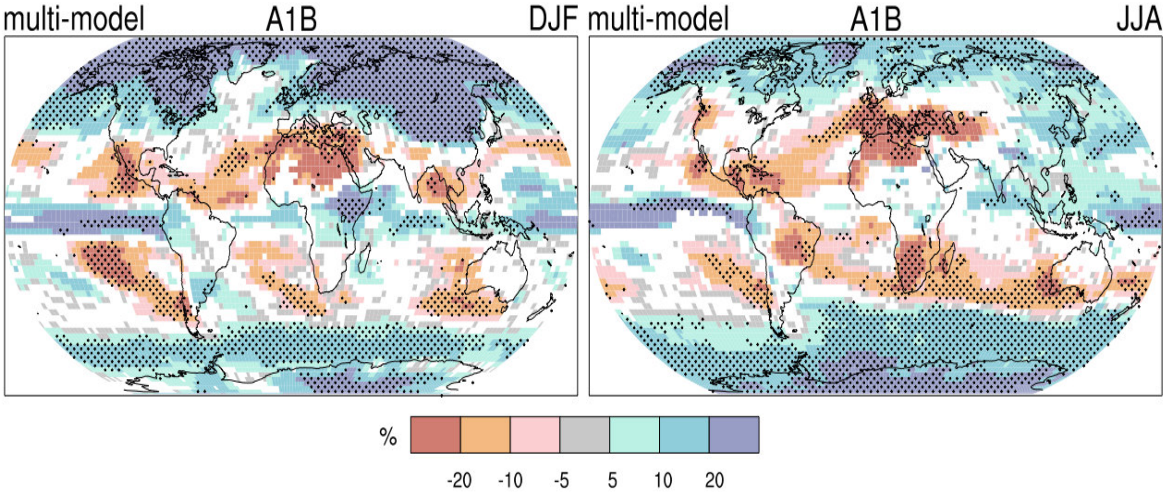

Fig. 1 Relative changes in precipitation for 2090–2099, relative to 1980–1999. Values are multi-model averages based on the A1B scenario for December–February (left) and June–August (right). White grid cells indicate areas where less than 66% of the models agree in the sign of the change, and coloured grid cells indicate areas where over 66% of the models agree in the sign of the change. Stippled grid cells represent areas where more than 90% of the models agree in the sign of the change (IPCC, 2007).

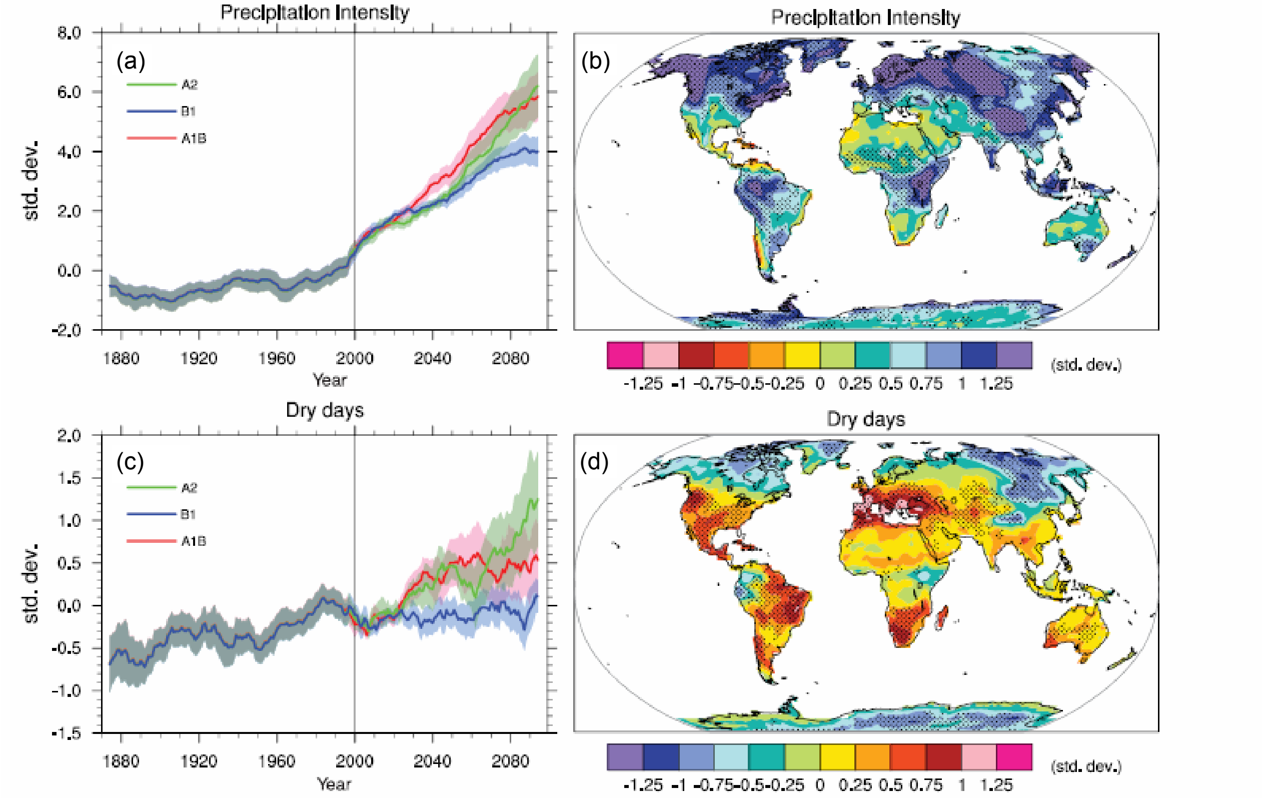

Fig. 2 Changes in extremes based on multi-model simulations from nine global coupled climate models, adapted from Tebaldi *et al.* (2006). (a) Globally-averaged changes in precipitation intensity for three scenarios. (b) Changes in spatial patterns of simulated precipitation intensity between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. (c) Globally-averaged changes in dry days (defined as the annual maximum number of consecutive dry days). (d) Changes in spatial patterns of simulated dry days between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. Solid lines in (a) and (c) are the 10-year smoothed multi-model ensemble means; the envelope indicates the ensemble mean standard deviation. Stippling in (b) and (d) denotes areas where at least five of the nine models concur in determining that the change is statistically significant. (Source: Meehl *et al.*, 2007; Figure 10.18).

recently been challenged by several scientists who admit the possibility of a much higher sea-level rise already in this century.

CLIMATE CHANGE IMPACTS ON FRESHWATER RESOURCES, IN PARTICULAR RIVER RUNOFF—OBSERVATIONS AND PROJECTIONS

According to Milly *et al.* (2008), in view of the magnitude and ubiquity of the hydroclimatic change apparently now under way, stationarity should no longer serve as a central, default assumption in water resources planning. The changes in temperature, and thus potential evapotranspiration (directly temperature-driven), and precipitation, affect freshwater resources significantly. An additional impact on river runoff stems from the widespread mass losses from glaciers and reductions in snow cover. Such changes, observed over recent decades, are projected to accelerate throughout the 21st century (Kundzewicz *et al.*, 2007).

Similar to precipitation, significant trends in some regional indicators of river flow have been found in some studies, but no globally homogeneous trend has been reported. In some regions, inter-annual variability of river flows is also very strongly influenced by large-scale atmospheric circulation patterns associated with El Niño-Southern Oscillations (ENSO), North Atlantic Oscillations (NAO) and other oceanic–atmospheric variability systems that operate at within-decadal and multi-decadal time scales. At a large scale, there is evidence of a broadly coherent pattern of change in annual river runoff, typically driven by precipitation change (Milly *et al.*, 2005). Many regions at higher latitudes of the Northern Hemisphere (such as southeastern to central North America, parts of western North America and northern Eurasia), the La Plata Basin of South America, the southeast quadrant of Africa and northern Australia have experienced runoff increase. Decrease in river runoff was observed in parts of West Africa, sub-Saharan Africa, southern Europe and southernmost South America. There is evidence of an earlier occurrence (by 1–2 weeks within the last 65 years in North America and northern Eurasia) of spring peak river flows, and an increase in winter baseflow in basins with important seasonal snow cover in North America and northern Eurasia (Rosenzweig *et al.*, 2007). As a result, there is a shift in peak river runoff away from summer and autumn, which are normally the seasons with the highest water demand.

Consistent with the precipitation projections, runoff is projected (Milly *et al.*, 2005; Nohara *et al.*, 2006) to increase by 10–40% by mid-century at higher latitudes and in some wet tropical areas, including populous areas in East and South-East Asia, and decrease by 10–30% over some dry regions at mid-latitudes and in the dry tropics, due to decreases in rainfall and higher rates of evapotranspiration. Water resources in many semi-arid areas (e.g. the Mediterranean Basin, western USA, southern Africa and Northeast Brazil) are projected to experience a decrease due to climate change. Drought-affected areas are projected to increase in extent. However, the uncertainty of these results is even higher than the uncertainty of projected precipitation changes.

The frequency of floods and droughts are projected to increase in the future, due to the increased precipitation variability (Kundzewicz *et al.*, 2007). The reliability of surface water supply is very likely to decrease due to higher temporal flow variations that stem from increased precipitation variability and reduced summer low flows in snow-dominated basins (Kundzewicz *et al.*, 2007).

The increase of heavy precipitation events, together with higher water temperatures, is also likely to exacerbate water quality problems, in particular by flushing pathogens and other pollutants (Kundzewicz *et al.,* 2007). In general, the negative impacts of climate change on freshwater systems outweigh any benefits (Kundzewicz *et al.*, 2007, 2008a).

CLIMATE CHANGE IMPACTS ON GROUNDWATER

The impact of climate change on groundwater has been studied much less than the impact on surface waters. Groundwater reacts to climate change mainly due to changes in diffuse groundwater recharge. Under certain circumstances (good hydraulic connection of river and aquifer, low rates of diffuse groundwater recharge), changes in river level influence groundwater levels more than changes in diffuse groundwater recharge (Allen *et al*., 2003). Besides, groundwater salinity in coastal areas may be increased by sea-level rise.

Where trends in river runoff have been identified, a similar trend in groundwater recharge is expected. However, due to lack of data, no ubiquitous climate-related trends for groundwater recharge or groundwater levels could be determined for the 20th century (Kundzewicz *et al.,* 2007). Observed declines in groundwater tables are mostly due to unsustainably high groundwater abstraction rates.

Impact of changes in mean climate

Due to crude representations of recharge processes in current climate models, the use of global hydrological models such as the WaterGAP Global Hydrology Model (WGHM, Döll & Fiedler, 2009) is necessary to arrive at projections of groundwater changes. According to this model, diffuse groundwater recharge (when averaged globally) will increase less in the future than total runoff (Döll & Flörke, 2005). While total runoff (groundwater recharge plus fast surface and subsurface runoff) was computed to increase by 9% between the reference climate normal (1961–1990) and the 2050s (for the ECHAM4 interpretation of the SRES A2 scenario), groundwater recharge would increase by only 2%. The land areas where total runoff is projected to increase (or decrease) roughly coincide with the areas where groundwater recharge is projected to increase (or decrease).

When considering four climate change scenarios (two climate models, two emissions scenarios), dramatic decreases in groundwater recharge are computed in some areas (even by more than 70%, by the 2050s as compared to the control period of 1961–1990), such as the Northeast of Brazil, southwestern Africa and along the southern rim of the Mediterranean Sea (Fig. 3, Döll & Flörke, 2005). The dramatic drop of recharge in Northeast Brazil was considered as an example of the most critical vulnerability globally (Kundzewicz *et al*., 2007, 2008a). In these areas of decreasing total runoff, the percentage decrease in groundwater recharge is higher than that of total runoff, which is due to the model assumption that in semi-arid areas groundwater recharge only occurs if precipitation exceeds a certain threshold. The system shows a strong amplification effect, with a small change in precipitation, inducing a larger change in recharge. However, there is much uncertainty in model-based projections and increased variability of daily precipitation was not taken into account in this study, so that the decrease of recharge in semi-arid areas may be somewhat overestimated. In some regions (e.g. in Spain and Australia), the differences in groundwater recharge caused by applying two different climate models for interpreting the same emissions scenario are larger than those caused by different emissions scenarios that are interpreted by the same climate model. In inland aquifers, a decrease in groundwater recharge can lead to saltwater intrusion of neighbouring saline aquifers (Chen *et al*., 2004), and increased evapotranspiration in semi-arid and arid regions may lead to the salinization of shallow aquifers.

Regions where groundwater recharge is projected to increase by more than 30% by the 2050s include parts of the Sahel, the Near East, Northern China, Siberia and the western USA (Fig. 3). The increases might be somewhat overestimated, as the increased occurrence of heavy rains, which leads to lower groundwater recharge due to infiltration limits, was not considered in the study by Döll & Flörke (2005). Although an increase in groundwater recharge increases the renewable groundwater resources, the resulting rising water tables may cause problems related to soil salinization, as has occurred in Australia (due not to climate change but to land-cover change, and to wet soils in towns or agricultural areas).

Hiscock *et al.* (2008) presented projections for groundwater recharge in Europe, using a broad range of scenarios of projected future climate until the end of the 21st century, in comparison with the 1961–1990 control period. Their results showed increases in annual potential groundwater recharge for northern Denmark (28%), southern England (32%) and northern France (60%), and decreases for northern Italy (22%) and southern Spain (78%). Hiscock *et al.* (2008) indicated that

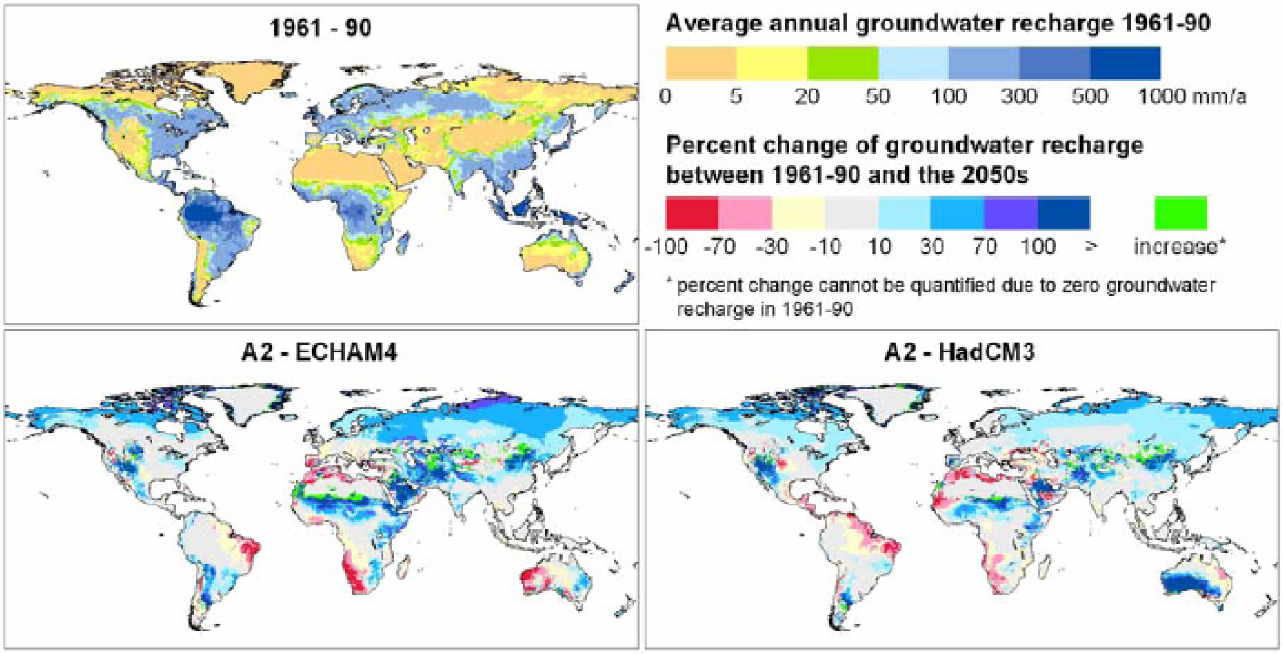

Fig. 3 Impact of climate change on long-term average annual diffuse groundwater recharge. Percent changes of average groundwater recharge between 30-year intervals, 1961–1990 and the 2050s (understood as a 30-year standard normal, centred on 2050s, i.e. 2041–2070), as computed by WGHM applying two different climate change scenarios (climate models ECHAM4 and HadCM3, each fed by IPCC greenhouse gas emissions scenario SRES A2, cf. Nakićenović & Swart (2000)). Modified after Döll & Flörke (2005).

the decrease in potential groundwater recharge in southern Europe as a result of climate change would seriously impact on the availability of freshwater resources for drinking and irrigation uses. The few studies of climate change impacts on groundwater for individual aquifers (e.g. in England, Belgium, Germany, Canada, Hungary and the USA) show site-specific and climate model-specific results.

In aquifers with significant seasonal snow cover, groundwater recharge might decrease due to there being less snow in a warmer world. This can be concluded from the fact that snowmelt provides at least 40–70% of groundwater recharge at four study sites in the southwestern USA, although only 25–50% of average annual precipitation falls as snow (Earman *et al*., 2006).

At high latitudes, thawing of permafrost causes changes in both the level and quality of groundwater due to increased coupling with surface waters. Climate change may lead to vegetation changes which also affect groundwater recharge.

Impact of increased precipitation variability

Groundwater resources are relatively more robust to increased climate variability, in comparison to surface water resources. Due to the buffering effect of groundwater storage, groundwater response to climate variability (or change) is slower than for the case of surface water systems. Deeper aquifers react, with delay, to large-scale climate change but not to short-term climate variability. Shallow groundwater systems (especially those in unconsolidated sediment or fractured bedrock) are more responsive to smaller-scale climate variability.

Increased precipitation variability may lead to changes in recharge. In semi-arid and arid areas, increased frequency and magnitude of intense precipitation, as well as of floods, may increase groundwater recharge, because only high-intensity rainfalls are able to infiltrate fast enough (e.g. in fractures and dissolution channels) before evaporating, and alluvial aquifers are recharged mainly by inundation due to heavy rainfalls and floods (Al-Sefry *et al*., 2004). However, in hydrophobic or cursted soils, infiltration during heavy rainfall is low (e.g. in the Sahel). In sub-humid and humid areas groundwater recharge may decrease because more frequent heavy precipitation events may result in the infiltration capacity of the soil being exceeded more often. A negative impact of increased heavy precipitation events on groundwater quality is the accelerated transport of pathogens to groundwater (Kundzewicz *et al*., 2007).

Impact of sea-level rise

The Ghyben-Herzberg relationship describes the location of the freshwater–saltwater interface as a function of the location of the groundwater table above sea level. If the groundwater table is one unit (e.g. metre, foot) above sea level, then the freshwater–saltwater interface is approximately 40 units below sea level. Thus, in coastal areas, a decrease in groundwater recharge (which causes a decrease in groundwater level) will cause salt water intrusion and a decrease in the depth of freshwater. Sea-level rise will cause the freshwater layer to move upwards to a new equilibrium with the new sea level, but the freshwater layer may become thinner as the water table approaches the soil surface, due to increased evapotranspiration and surface runoff and thus decreased groundwater recharge. This is problematic, particularly in low-elevation areas such as deltas and coral islands.

Using a finite-element groundwater flow model and applying the Ghyben-Herzberg assumption, Bobba *et al.* (2000) computed how sea-level rise would affect the depth of the freshwater lenses of two small coral islands off the coast of India (Laccadives), the elevation of which is mainly between 2 and 4 m a.s.l. The maximum depths of the freshwater lens in the centre of the islands were calculated to decrease from 25 m to 10 m and from 36 m to 28 m for a sea-level rise of 0.1 m, which is virtually certain in a couple of decades. This was considered as one of the global examples of most critical vulnerability (Kundzewicz *et al*., 2007, 2008a). Note that the Ghyben-Herzberg relationship overestimates the volume of available freshwater as it does not account for the large mixing zone that typically occurs due to tidal movements and other reasons. Together with the seasonal dynamic of the groundwater table due to precipitation and evapotranspiration, and the drawdown of the water table due to pumping, the sea-level rise that is likely to occur during the 21st century might leave many flat coral islands without a source of reliable groundwater (or other freshwater), so that costly and energy-consuming desalination will be needed.

CONCLUSIONS

Climate change affects groundwater mainly due to changes in groundwater recharge (and the resulting water table changes). Where groundwater recharge decreases in semi-arid and coastal regions, groundwater salinity may increase. Flat areas such as deltas and coral islands are expected to suffer from sea-level rise due to saltwater intrusion and thus decreased freshwater availability. Negative impacts on pathogens are also expected due to increased heavy precipitation events. However, quantitative estimates of these impacts are highly uncertain.

We expect that reliable surface water availability will decrease, or only marginally increase, in most regions of the world, due to lower long-term average total runoff and/or higher temporal flow variations that stem from increased precipitation variability and reduced summer low flows in snow-dominated basins (Kundzewicz *et al*., 2007). Given the higher storage capacity of groundwater as compared to surface water in rivers, we hypothesize that use of groundwater could ease freshwater stress under climate change. Where will this be possible, assuming that the demand for water will increase in all countries except for a few OECD countries (until the 2050s)? In the following, we attempt a preliminary answer to this difficult question.

Particularly in areas where water demand increases, groundwater withdrawals are very likely to increase in the future. In addition, groundwater withdrawals as a fraction of total human water withdrawals are likely to increase where surface water becomes scarcer, due either to increased surface water withdrawals, or to less reliable surface water supply caused by climate change and increasing variability of precipitation and river flow. However, increased groundwater withdrawals are not sustainable if quantities are not much less than groundwater recharge to avoid (i) harmful reductions in baseflow to surface water bodies and (ii) large drawdowns of the groundwater table which could have negative effects on groundwater-dependent ecosystems.

In all those areas where not only surface water availability but also groundwater recharge is reduced due to climate change (Fig. 3), the opportunities to balance the effects of more variable surface water flows by groundwater use are restricted. To identify areas with non-decreasing groundwater resources, where groundwater could ease freshwater stress under climate change, some snow-impacted areas might have to be subtracted from the respective areas in Fig. 3, as well as areas with insufficient groundwater quality due to salinity or anthropogenic or natural pollution (e.g. areas of high arsenic and fluoride concentration in India, China and other yet to be identified areas). Besides, only scattered small-scale groundwater pumping will be possible in those 50% of the continental areas where exploitable groundwater resources are restricted to shallow or local aquifers (www.whymap.org).

To take advantage of the natural storage capacity provided by aquifers, the artificial recharge of groundwater is an option that should be further explored. Methods include well injections, recharge dams, induced river bank infiltration and spreading methods (www.igrac.nl/publications/155). The applicability of artificial recharge is restricted by the availability of aquifers with a high transmissivity and storage capacity, and by different geochemical compositions of surface waters and groundwater which can lead to technical difficulties like well clogging.

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