Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment

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Abstract
Climate change will lead to significant changes of groundwater recharge and thus renewable groundwater resources. Using the global water resources and use model WaterGAP, the impact of climate change on groundwater recharge and the number of affected people was computed for four climate scenarios by two climate models. Vulnerability of humans to decreased groundwater resources depends on both the degree of decrease and the sensitivity of the human system to the decrease. For each grid cell, a sensitivity index composed of a water scarcity indicator, an indicator for dependence of water supply on groundwater and the Human Development Index was quantified. Combining per cent groundwater recharge decrease with the sensitivity index, global maps of vulnerability to the impact of decreased groundwater recharge in the 2050s were derived. In the A2 (B2) emissions scenario, 18.4–19.3% (16.1–18.1%) of the global population of 10.7 (9.1) billion would be affected by groundwater recharge decreases of at least 10%, and 4.8–5.7% (3.8–3.8%) of the global population would be in the two highest vulnerability classes. The highest vulnerabilities are found at the North African rim of the Mediterranean Sea, in southwestern Africa, in northeastern Brazil and in the central Andes, which are areas of moderate to high sensitivity. For most of the areas with high population density and high sensitivity, model results indicate that groundwater recharge is unlikely to decrease by more than 10% until the 2050s. However, a fifth to a third of the population may be affected by a groundwater recharge increase of more than 10%, with negative impacts in the case of shallow water tables. The spatial distribution of vulnerability, even at the continental scale, differs more strongly between the two climate models than between the two emissions scenarios.

Keywords: vulnerability, climate change, groundwater, global, scenario, sensitivity index

1. Introduction
It is vital to determine human vulnerability to the impact of climate change on groundwater because groundwater is an important resource for human water supply, and it is likely to become even more important under future climatic conditions. In the future, precipitation variability will increase and snow/ice storage will decrease, causing increased streamflow variability with decreased low flows and thus decreased surface water reliability (Kundzewicz et al 2007, 2008). Which fraction of global freshwater use currently stems from groundwater is not well known. Zektser and Everett (2004) estimated that globally 50% of domestic water supply, 40% of water withdrawals for self-supplied industry and 20% of irrigation water supply is from groundwater. In the European Union the groundwater supply fraction of domestic water use is approximately 70%, and in many semi-arid countries (e.g. India, USA, Mexico and Australia) more than one third of irrigation water is pumped from the ground (Zektser and Everett 2004). Groundwater is a particularly
important source of drinking water in rural areas. Advantages of groundwater use as compared to surface water use are the better protection of groundwater from pollution and the (sometimes) better accessibility because groundwater bodies are spatially more extensive than surface water bodies, thus allowing withdrawals close to the users. Besides, groundwater availability is temporally much more even than surface water availability (except in the case of large lakes and reservoirs). Groundwater bodies serve as large natural ‘reservoirs’ which allow water withdrawals even at times when surface water availability is low, i.e. in the dry season or during long interannual droughts. In addition, a more gradual and thus flexible development of the water resources is possible by the sequential installation of groundwater wells, as compared to the mostly larger surface water schemes (including reservoir construction). However, groundwater resources are more difficult to identify, assess and monitor than surface water resources, and well construction and pumping costs may be high.

Groundwater resources can be considered in terms of water volume, i.e. groundwater storage, or in terms of water flow, i.e. groundwater recharge, the water flow that recharges the groundwater store. Long-term average groundwater recharge is thus a measure of the ‘renewable’ groundwater resources. To achieve a sustainable groundwater use, by which groundwater is not depleted, groundwater withdrawals may not exceed long-term average groundwater recharge. If withdrawals exceed recharge, groundwater storage and levels continue to decline. Such groundwater depletion has occurred in particular in semi-arid and arid regions with little (present-day) groundwater recharge but large so-called ‘fossil’ or ‘non-renewable’ groundwater resources that developed during more humid climate periods. An example is the Nubian Aquifer in Libya, Egypt and Sudan.

Kundzewicz and Döll (2009) provided an overview of the impacts of climate change on groundwater. The assessment presented in this paper is restricted to the impact of climate change on long-term average groundwater recharge as a measure of renewable groundwater resources. The sensitivity of the human system to a change of groundwater recharge depends, at least in the case of decreasing groundwater recharge, on the relative importance of groundwater resources and use as compared to other freshwater resources and use, and on total human water use, from both surface water and groundwater. Table 1 gives an overview of global renewable freshwater resources and use, distinguishing three types of resources: (1) the basic resource precipitation, (2) the part of the precipitation that becomes runoff and (3) the part of total runoff that recharges the groundwater. The term ‘renewable water resources’ generally refers to long-term average runoff (i.e. precipitation minus evapotranspiration), while the term ‘renewable groundwater resources’ refers to long-term average groundwater recharge. Renewable water resources are also called renewable blue water resources, to distinguish them from green water resources, i.e. the part of the precipitation water that evapotranspires on agricultural land and thus is a resource for crop growth. Using version 2.1f of the WaterGAP Global Hydrological Model WGHM, renewable groundwater resources, 12,600 km² yr⁻¹, were calculated to account for one third of the total renewable blue water resources (Döll and Fiedler 2008). Human use of the total blue water resource (including non-renewable water resources) is dominated by irrigation, which accounts for 70% of global water withdrawals and more than 90% of global consumptive water use (table 1). Without irrigation, global cereal production would decline by 20% (Siebert and Döll 2009). According to our own preliminary estimation, about one fourth of global water withdrawals stem from groundwater (table 1).

Following the definition of IPCC (2007, p 883), vulnerability to climate change ‘is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, . . .’ and is ‘a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity’. Adaptive capacity is the ‘ability of a system to adjust to climate change (. . .) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences’ (IPCC 2007, p 869). In their ‘framework of vulnerability to climate change’, Ionescu et al (2009) state that ‘accurate statements about vulnerability are possible only if one clearly specifies (1) the entity that is vulnerable, (2) the stimulus to which it is vulnerable and (3) the preference criteria to evaluate the outcome of the interaction between the entity and the stimulus.’ In this paper, the vulnerable entity is the total

| Type of freshwater resources or use                  | Water flows (km² yr⁻¹) |
|-----------------------------------------------------|------------------------|
| (1) Water resources: precipitation on land surfaces of the Earth (without Antarctica) | 104 700                |
| (2) Water resources: water use: evapotranspiration of precipitation on agricultural land | 5300                   |
| (2) Water resources: runoff (renewable freshwater resources) | 38 800                 |
| (2) (Blue) water use: total water withdrawals (consumptive water use) | 4020 (1 300)           |
| Thereof for irrigation                               | 2900 (1200)            |
| for households                                       | 340 (50)               |
| for manufacturing                                    | 250 (40)               |
| for cooling of thermal power plants                  | 530 (10)               |
| (3) Water resources: groundwater recharge (renewable groundwater resources) | 12 600                 |
| (3) Water use: groundwater withdrawals               | 1100                   |
population living in a 0.5° latitude by 0.5° longitude grid cell; different population groups (rich and poor, men and women etc) are not distinguished. The stimulus is the change of long-term average groundwater recharge GWR (i.e. renewable groundwater resources) between the time period 1961–90 and time period 2041–2070 (‘the 2050s’) that is caused by different scenarios of climate change. Other impacts of climate change on groundwater, e.g. impacts on groundwater quality, are not taken into account. The preference criterion is that no change in GWR is considered to be best. While a decrease in GWR and thus renewable groundwater resources may cause water supply problems for humans (and ecosystems), an increase in GWR may lead to an unwanted rise of the groundwater table. In particular if the groundwater table is already close to the soil surface (<2 m), increased GWR may cause infrastructure damage (e.g. of buildings and pipes), soil and groundwater salinization, and wet soils which make it difficult to work the land in agricultural areas. However, in particular in water-scarce areas, increasing GWR has a positive impact on water supply. This ambiguity makes it impossible to determine vulnerabilities to increasing GWR in a global-scale assessment. Decreasing GWR has a clear negative effect on renewable groundwater resources and water supply such that this paper focuses on the vulnerability to decreasing GWR.

Having defined the system/entity of interest to be the population that depends on groundwater resources and not the physical groundwater system itself, the sensitivity of the system to climate change includes not only the impact of climate change on renewable groundwater resources but also the sensitivity of the population to the decreased groundwater resources. While sensitivity of the groundwater system to climate change can be modelled by a hydrological model driven by climate variables that reflect climate change, the sensitivity of the population has to be approximated by indicators. Likewise, adaptive capacity is generally quantified by indicators, which often include gross domestic product (e.g. Metzger et al 2008).

The impact of climate change on renewable groundwater resources (or GWR) was quantified, at the global scale, by Döll and Flörke (2005) using the WaterGAP Global Hydrological Model WGHM, and the results were included and discussed in the IPCC Fourth Assessment Report (Kundzewicz et al 2007, their figure 3.5). Other global-scale assessments of the climate change impact on GWR are not yet available. For this paper, the impact of climate change on GWR was recalculated with the most recent model version 2.1f (Hunger and Döll 2008, Döll and Fiedler 2008), considering the IPCC SRES scenarios A2 and B2 (Nakicenovic and Swart 2000). In addition, the number of people affected by future GWR changes in these scenarios is presented for the first time, looking at the 2050s. Moreover, taking into account selected indicators for sensitivity and adaptive capacity of the human system, the vulnerability of humans to decreasing renewable groundwater resources caused by climate change is assessed in a quantitative and a spatially explicit manner for the whole globe. Vulnerability is expressed as an ‘index of human vulnerability to climate change induced decreases of renewable groundwater resources’ VI.

In section 2, the methods to compute VI are described. These methods include modelling of the changes in groundwater resources due to climate change and modelling of the sensitivity and adaptive capacity of the human system. In sections 3 and 4, results are presented and discussed. Finally, conclusions are drawn.

2. Methods

The index of human vulnerability to climate change induced decreases of renewable groundwater resources VI is defined as

\[
VI = -\% \text{ change GWR} \times SI \\
\text{if } % \text{ change GWR } \in [-100; -10] \\
\text{otherwise VI is not defined}
\]

with \(SI = \text{mean}(SI_{\text{WS}}, SI_{I}, SI_{G})\) (1)

where GWR denotes long-term average groundwater recharge in \(\text{mm yr}^{-1}\). SI is the sensitivity index, \(SI_{\text{WS}}\) is an indicator for water scarcity, \(SI_{I}\) is an indicator for the dependence of water supply on groundwater, and \(SI_{G}\) is an indicator representing the generic, not water-related sensitivity or adaptive capacity of the human system (at the macro-scale). In this study, the vulnerability index VI is defined only where GWR decreases strongly by at least 10% in the respective scenario. This approach was chosen to avoid overestimating vulnerability, given the uncertainty of WGHM. Please note that the term ‘index’ refers to the mathematical aggregation of indicators or variables, often across different measurement units (WWAP 2003, p 33).

In this study, the sensitivity of the human system to decreases of GWR is assumed to be high if the system suffers from water scarcity, and if a large part of water supply is taken from groundwater. In addition to these water-related reasons for sensitivity, it is assumed that a poor society with a low educational level will be more sensitive and will have a lower adaptive capacity than a rich society with a high educational level. The sensitivity indicators can vary between 1 and 5, with 1 representing minimum sensitivity (or maximum adaptive capacity), and 5 representing maximum sensitivity (or minimum adaptive capacity). The definition of VI as given in equation (1) aims at representing clearly the climate change impact on GWR, i.e. the physical system. SI serves to ‘exaggerate’ the change of GWR as a function of the sensitivity and adaptive capacity of the human system at each location (grid cell). For grid cells in which sensitivity of the human system is very small (SI = 1), VI is equal to the per cent GWR decrease, while in cells with maximum sensitivity (SI = 5), VI will be five times the per cent GWR decrease. The sensitivity indicators were evaluated only for current conditions, not for future conditions. The quantification of the variables in equation (1) is described below.

2.1. Modelling the physical system

The next two sections explain how GWR and its change due to climate change (% change GWR in equation (1)) were computed.
2.1.1. Groundwater recharge. With a spatial resolution of 0.5° by 0.5° (55 km by 55 km at the equator), the global water resources and use model WaterGAP simulates both global hydrology and water use in the sectors irrigation, livestock, households, manufacturing and cooling of thermal power plant for all land areas of the Earth excluding Antarctica (Alcamo et al. 2003). The WaterGAP Global Hydrology Model WGHM computes GWR, total runoff as well as river discharge taking into account the impact of human water use on river discharge. It is tuned in a basin-specific manner against long-term average discharge at 1235 gauging stations (Hunger and Döll 2008, Döll et al. 2003). Important WGHM inputs are time series of monthly values of climate variables as well as information on soil and land cover. Monthly climate data are downscaled to daily data, in the case of precipitation using the available number of wet days per month. As precipitation input, 0.5° gridded monthly time series of the GPCC Full Data Product Version 3 (Rudolf 2005) were used, together with the number of wet days from the CRU TS 2.0 data set (Mitchell and Jones 2005). Because precipitation is the most important model input, and uncertainty of global precipitation data sets is high, we additionally ran the model with the 1961–1990 time series of monthly precipitation of the CRU TS 2.0 data set, and could thus compare the precipitation-related uncertainty of computed GWR with the computed GWR change due to climate change.

GWR is determined by partitioning total runoff from land in each grid cell, taking into account relief, soil texture, hydrogeology and the existence of glaciers and permafrost (Döll and Fiedler 2008). GWR is assumed to be constrained by a maximum daily groundwater recharge rate, which is a function of soil texture. In semi-arid and arid areas, this algorithm lead to a consistent overestimation of GWR compared to independent point estimates of GWR. In these areas GWR is assumed to occur, in case of medium to coarse grained soils, only if daily precipitation exceeds 10 mm d⁻¹. This leads to an unbiased GWR estimation (Döll and Fiedler 2008). WGHM only simulates GWR from land (diffuse recharge via the soil) but neglects point recharge from surface water bodies. At the grid cell level, uncertainty of computed GWR is high, in particular due to the uncertain precipitation, but broad-scale patterns and values have been found plausible by experts who checked the global WaterGAP groundwater recharge map before it became a layer of the Groundwater Resources of the World map of UNESCO’S WHYMAP effort (www.whymap.org, Döll and Fiedler 2008).

2.1.2. Impact of climate change on groundwater recharge. In this study, four different climate change scenarios were taken into account, looking at the situation in the 2050s. The two IPCC greenhouse gas emissions scenarios A2 and B2 (Nakicenovic and Swart 2000) were translated into climate change scenarios by two state-of-the-art global climate models, the ECHAM4/OYP/C3 model (Röckner et al. 1996, hereafter referred to as ECHAM4) and the HadCM3 model (Gordon et al. 2000), resulting in four climate change scenarios. In the A2 scenario, emissions increase from 11 Gt C yr⁻¹ (CO₂-equivalent) in 1990 to 25 Gt C yr⁻¹ in the 2050s, but only to 16 Gt C yr⁻¹ in the case of scenario B2. Due to large climate model uncertainties, the same emissions scenarios are translated to rather different climate scenarios, in particular with respect to precipitation.

The changes in averages of monthly precipitation and temperature values between the periods 1961–1990 and 2041–2070 as computed by the climate models were used to scale the grid cell values of observed monthly precipitation (GPCC) and temperature between 1961 and 1990 that drive WGHM in the control run. In a first step, the climate model data were interpolated from their original resolutions to the WGHM resolution of 0.5°. Then, in the case of temperature, observed values were scaled by adding to them the difference of the climate model values of future (2041–2070) and present-day (1961–1990) temperature, while the 30 yr perturbed precipitation time series was produced by multiplying observed values with future climate model precipitation as a ratio of the present-day precipitation. If present-day monthly precipitation was less than 1 mm, precipitation was scaled additively, like temperature. The impact of the predicted increased variability of daily precipitation was not taken into account in this study.

2.2. Modelling the human system

To assess the number of people affected by changes in GWR as well as the vulnerable population, population numbers in each 0.5° grid cell are required. For the scenarios, 0.5° gridded population scenarios for A2 and B2 in 2050 and 2060 as provided by Van Vuuren et al. (2007) were averaged to obtain an estimate for the 2050s. These scenarios are based on population scenarios for 17 world regions that were downscaled to the country level using UN national population projections. Downscaling to the grid scale was done by applying the national changes to the population in each grid cell from CIESIN GPWv2 population data (CIESIN 2003). In the following, the methods for quantifying the sensitivity indicators are described.

2.2.1. Indicator for water scarcity S_WS.

The most widely used indicators for water scarcity are (1) per-capita water resources and (2) water withdrawal-to-availability ratio (water withdrawals divided by long-term average water resources). The first indicator does not take into account that water demand varies significantly among regions. None of the two indicators consider seasonal or interannual variability of water supply. They thus overestimate water availability in semi-arid areas relative to humid areas, as semi-arid areas have a much stronger temporal flow variability. In this study, the ratio of consumptive water use to statistical low flow Q₉₀ is the monthly river discharge that is exceeded in 9 out of 10 months, and is computed for the time period 1961–90 using WGHM. Consumptive use CU is the fraction of the withdrawn water that does not return to the river or groundwater but is evapotranspired, thus causing flow reductions. To compute the indicator, annual CU is divided by 12 to make it compatible to the monthly value Q₉₀. Sectoral CU values were computed by the various water use models as the average value of the
time period 1998 to 2002, and then added. Irrigation water use, which accounts for more than 90% of consumptive use globally, was computed according to Döll and Siebert (2002) using as input the climate time series 1998–2002, version 4.0.1 of the Global Map of Irrigated Areas GMIA (Siebert et al 2005) and estimates of actually irrigated area per country and year. If $CU/Q_{90}$ is larger than one, one twelfth of annual consumptive water use exceeds river discharge in 1-in-10 low flow months. During these months, water could be taken from groundwater or reservoirs, or water use must be restricted.

### 2.2.2. Indicator for dependence of water supply on groundwater $S_{DGW}$

We recently compiled data on groundwater withdrawals in countries or subnational units from a large number of data sources (e.g. from the International Groundwater Resources Assessment Centre IGRAC). For this study, a preliminary estimate of groundwater withdrawals as a fraction of total water withdrawals per country or subnational unit $f_g$ was derived and applied to quantify $S_{DGW}$. For a few countries, $f_g$ had to be estimated from values for surrounding countries. It is not well known for which time period the statistical data are representative, but $f_g$-values may be assumed to be indicative of the situation around the year 2000.

### 2.2.3. Indicator for generic sensitivity or adaptation capacity of the human system $S_G$.

The Human Development Index HDI was selected as indicator for the generic, not specifically water-related sensitivity of the population. HDI can also be interpreted as a generic indicator for adaptive capacity. It includes three dimensions: life expectancy at birth, a combination of adult literacy rate and school enrolment, and per-capita gross domestic product in purchasing power parity terms in US dollars. HDI is computed for individual countries. We used the HDI values for 2006 (UNDP 2008) available for 179 countries and territories. HDI values range between 0.329 (Sierra Leone) and 0.968 (Iceland and Norway). The HDI of 179 countries and territories. HDI values range between 0.329 (Sierra Leone) and 0.968 (Iceland and Norway). The HDI of 179 countries and territories. HDI values range between 0.329 (Sierra Leone) and 0.968 (Iceland and Norway).

### 2.2.4. Computation of $SI$

In order to calculate $SI$ with equation (1), its three components $SI_{WS}$, $SI_{DGW}$ and $SI_G$ have to be derived from $CU/Q_{90}$, $f_g$ and HDI, respectively. This was done by first distributing the value range of $CU/Q_{90}$, $f_g$ and HDI into five classes and then mapping these classes onto $SI$ component values of 1, 2, 3, 4 and 5, respectively (table 2). The original values were not linearly mapped onto the range between 1 and 5 because the classification and mapping as done in table 2 allowed for a subjective expert judgement on the relation between original indicator values and sensitivity (or adaptive capacity). Besides, for water scarcity indicators, mapping of indicator values into no stress, low stress classes etc is common. The water scarcity indicator $CU/Q_{90}$ is not defined in grid cells where $Q_{90}$ is zero, which occurs in many semi-arid and arid grid cells (or some very cold grid cells). In this case, $SI_{WS}$ was set to 1 if consumptive use in the whole grid cell was less than 1000 m$^3$/month, and to 5 elsewhere.

### 3. Results

#### 3.1. Estimates of GWR changes due to climate change, and of affected population

Figure 1 shows how climate change may alter GWR and thus renewable groundwater resources until the 2050s. The spatial pattern and intensities of changes vary with the emissions scenario and the climate model used to translate emissions into changes of climatic variables. However, all scenarios agree broadly in that GWR will increase in northern latitudes, but will decrease strongly, by 30–70% or even more than 70%, in some currently semi-arid zones, including the Mediterranean, northeastern Brazil and southwestern Africa. The spatial pattern of increases and decreases of groundwater recharge are consistent with the spatial pattern of total runoff changes.

By the 2050s, GWR may have decreased by more than 10% on 20.4–21.5% (depending on the climate model) of the global land area for emissions scenario A2, and on 18.3–20.4% for scenario B2 (table 3). 18.4–19.3% of the global population of 10.7 billion in 2055 may suffer from such significant decreases in scenario A2, and 16.1–18.1% of the global population of 9.1 billion in scenario B2. About 110 million people may be affected by a decrease of GWR of more than 70% in A2, and 30–70 million people in B2 (table 3). A smaller percentage of the global population may suffer from GWR decreases of more than 30% in B2 than in A2 (4.3–4.5% versus 6.2–6.4%). 43.7–60.4% of the global population may only be affected by small GWR changes of less than 10%, and the values differ more strongly due to climate model uncertainty than due to the different emissions scenarios. By 2055, 26.5–37.7% of the population may have been exposed to an increase of GWR of more than 10% in A2, while...
Figure 1. Impact of climate change on long-term average groundwater recharge GWR in the 2050s. Long-term average 1961–1990 groundwater recharge, in mm yr\(^{-1}\), and per cent changes between 1961–1990 and 2041–2070, as computed by WGHM applying four different climate change scenarios (climate scenarios computed by the climate models ECHAM4 and HadCM3, each interpreting the IPCC greenhouse gas emission scenarios A2 and B2).

Table 3. Areas (in % of global land area except Antarctica and Greenland) and population affected by changes in groundwater recharge between 1961–1990 and 2041–2070, for four climate change scenarios.

| GWR change (%) | ECHAM4 A2 | HadCM3 A2 | ECHAM4 B2 | HadCM3 B2 |
|----------------|-----------|-----------|-----------|-----------|
|                 | % of global land area | % of global pop. in 2055 | % of global land area | % of global pop. in 2055 | % of global land area | % of global pop. in 2055 | % of global land area | % of global pop. in 2055 |
| −100 to −70     | 2.8       | 1.0       | 2.2       | 1.0       | 2.5       | 0.8       | 1.8       | 0.4       |
| −30 to −70      | 6.0       | 5.2       | 7.6       | 5.4       | 4.7       | 3.7       | 6.3       | 3.9       |
| −10 to −30      | 11.6      | 12.2      | 11.9      | 12.9      | 10.1      | 13.6      | 12.3      | 11.8      |
| −10–10          | 33.3      | 43.7      | 39.1      | 54.0      | 35.5      | 44.7      | 42.9      | 60.4      |
| 10–30           | 17.7      | 19.2      | 20.9      | 15.1      | 18.1      | 19.4      | 20.2      | 14.5      |
| 30–70           | 16.8      | 10.8      | 10.0      | 7.3       | 17.5      | 10.2      | 9.6       | 5.4       |
| >70             | 10.4      | 7.7       | 7.2       | 4.1       | 10.4      | 7.4       | 5.9       | 3.6       |
| Increase from 0 | 1.4       | 0.2       | 1.0       | 0.1       | 1.3       | 0.2       | 1.0       | 0.1       |

the corresponding numbers are 23.5–37.0% in B2 (table 3). However, as discussed in the introduction, GWR increases may but need not be beneficial. The ECHAM4 climate model predicts much more extensive areas with significantly increased precipitation than the HadCM3 model, but almost the same extent of drier areas.

At the continental scale, the fractions of the European, North American and Asian population that may suffer from extreme decreases of GWR of more than 70% are smaller than the global average (not shown). This is also true for Australia in the case of the HadCM3 climate model. According to the HadCM3 but not the ECHAM4 model, Europe is the continent with the largest fraction of population that will only be affected by a small (10%) change in GWR, followed by Asia. In general, the differences between the two climate models are much stronger at the continental than at the global scale so that a general ranking of continents with respect to the degree of impact is not possible.

3.2. Estimates of sensitivity and vulnerability

Figure 2 shows the three different indicators for sensitivity and adaptive capacity together with the combined sensitivity index SI. The grid-scale water scarcity indicator \(CU/Q_{90}\)
Figure 2. Water scarcity indicator: consumptive water to Q90 ratio CU/Q90 (a), indicator for water supply dependence on groundwater: groundwater withdrawals to total water withdrawals ratio fg (b), indicator for general sensitivity and adaptive capacity: Human Development Indicator HDI (c), and the resulting sensitivity index SI (d). Legend classes for (a)–(c) correspond to sensitivities classes (comp. table 2).

shows high values in semi-arid and arid areas with mostly high consumptive use due to irrigation (figure 2(a)). Water supply dependence on groundwater fg varies strongly among countries and, in particular, among subnational units, indicating that spatially more highly-resolved information on fg would lead to very heterogeneous and localized distribution of fg (figure 2(b)). The country-scale indicator for general sensitivity and adaptive capacity HDI shows high values, i.e. low sensitivity and high adaptive capacity, in industrial countries and low values in most African and some Asian countries (figure 2(c)). SI, the mean of these three indicator values per grid cell, is highest (between 4 and 5) in most grid cells of India, Pakistan, Iran, Saudi Arabia, Jordan, Morocco and Tunisia, and in eastern China around Beijing. In addition, the Sahel Zone and smaller areas in Africa and the Arabian Peninsula show high SI-values (figure 2(d)). All these areas suffer from strong water scarcity, take more than 30% of their water supply from groundwater and have a low to medium HDI of less than 0.8. Areas with SI = 3–4 include Mongolia, Afghanistan, many African countries, large parts of northern China, India, Bangladesh, the Near East and Turkey, as well as semi-arid regions in Mexico, Canada and the Southwest of the USA. Also grid cells in Australia are affected. In Canada, the USA, and Australia, the high HDI attenuates high water scarcity and dependence on groundwater. 23% of the global population belong to the highest sensitivity class (SI = 4–5), 31% to the second but highest class (3–4), 30% to the second but lowest and 16% to the lowest sensitivity class.

In scenario ECHAM4 A2, for example, 27% of the global population in the lowest sensitivity class (1–2) will have suffered, in 2055, from a decrease of groundwater recharge of more than 10% (table 4). The corresponding numbers for the higher sensitivity classes are 26%, 16% and 6%. Thus, among the population that is most sensitive to decreases in groundwater recharge, the percentage of people that might actually suffer from GWR decrease is lower than among the less sensitive population. This relation is due to the spatial distribution of projected groundwater recharge changes. In India and also China, where population numbers and sensitivity are high, groundwater recharge will increase according to our calculation, while ECHAM4 A2 shows very strong GWR decreases in Europe as compared to the other three scenarios (figure 1). In the highest impact class, with GWR decreases of more than 70%, all sensitivity classes are affected to a similar degree. Overall, 18% of the global population will be affected by a decrease of more than 10% in scenario ECHAM4 A2, compared to 18% that will be affected by a less significant decrease between 0 and 10%.

The spatial pattern of the vulnerability index VI differs more between the two climate models (for the same emissions scenario) than between the two emissions scenarios (figure 3). However, all scenarios agree that vulnerability is very high at the North African rim of the Mediterranean Sea, in western Africa, in northeastern Brazil and in the central Andes. Western Australia is also very vulnerable, but only in the ECHAM4 scenarios, while Central America is vulnerable only in the HadCM3 scenarios.

In the A2 (B2) emissions scenario, 4.8–5.7% (3.8–3.8%) of the global population of 10.7 (9.1) billion would be in the two highest vulnerability classes (VI > 100) (figure 4). In the ECHAM4 A2 climate change scenario, Europe and Australia/Oceania are the two continents with the highest
Figure 3. Vulnerability index VI showing human vulnerability to climate change induced decreases of renewable groundwater resources by 2055 for four climate change scenarios. VI is only defined for areas with a GWR decrease of at least 10%.

Table 4. Number of people with different sensitivities to GWR decrease in scenario A2 (ECHAM4), in per cent of population in SI class.

| Sensitivity index SI | 1–2 | 2–3 | 3–4 | 4–5 |
|---------------------|-----|-----|-----|-----|
| Total population in SI class, in % of global population | 16.0 | 29.7 | 30.9 | 23.4 |
| GWR decrease >10%, in % population in SI class | 26.7 | 25.9 | 16.0 | 6.4 |
| GWR decrease >30%, in % population in SI class | 4.5 | 6.2 | 7.8 | 5.1 |
| GWR decrease >70%, in % population in SI class | 1.1 | 1.0 | 1.0 | 0.7 |

fractions of vulnerable people. In the HadCM3 A2 climate change scenario, the ranking of continents according to their vulnerable population fractions is markedly different, and Europe has the second but lowest fraction of the population that is vulnerable (figure 4). North America (including Central America), has the lowest vulnerability in ECHAM4 A2, with less than 10% of its population being identified as vulnerable, but this value reaches 40% in HadCM3 A2. For Australia/Oceania, the total number of vulnerable people is higher in case of HadCM3, but there are no or almost no people in the two highest vulnerability classes.

4. Discussion

4.1. Selection of indicators and indices

The UN’s ‘World Water Assessment Programme’ considers indicators as vital instruments in macro-scale water-related assessments and supports an ongoing process of developing better indicators. ‘Indicators help to reflect and communicate a complex idea’ and they ‘are our link to the world’ (WWAP 2003, p 33). In this study, an indicator for vulnerability to climate change induced decreases of renewable groundwater resources (VI) was defined and quantified. Compared to the Water Poverty Index (Sullivan et al 2003) and the similar Climate Vulnerability Index (Sullivan and Meigh 2005), which express the general vulnerability of human communities in relation to water resources, VI is a rather specific indicator of vulnerability to a specific climate change impact. The two indices of Sullivan and colleagues are therefore more comparable to the sensitivity index SI. However, here SI was specifically designed to be combined with the impact of climate change on groundwater resources. The other two indices are very general ones that keep with the sustainable livelihoods approach used by donor organizations to evaluate development progress.

In this study, sensitivity of the human system and adaptive capacity are assumed to depend only on the current situation of the system. However, vulnerability to the impacts of climate change certainly depends also on future sensitivity (e.g. related to future water demands and availability of surface water supply) and future adaptive capacity. Existing scenarios of water use and gross domestic product in the 2050s could have been taken into account for assessing vulnerability in this study, while scenario estimates of future availability of surface water supply or future groundwater exploitation are not available yet. However, even including scenarios of water demands and gross domestic product would have strongly increased complexity. By introducing the additional assumptions of such scenarios, this study would have become less transparent, i.e. the resulting vulnerabilities would have
been more difficult to understand. Here, only population scenarios are used.

With respect to the water scarcity indicator, one might consider to use the ratio of groundwater withdrawals to renewable groundwater resources. However, estimates of this ratio are currently only possible for countries (at least in global-scale analysis) but not at the grid scale. Besides, this indicator would be recommendable only as a second water scarcity indicator since total water demand (from surface or groundwater) as included in \( CU/Q_{90} \) impacts the sensitivity of the human system particularly under conditions of decreasing surface water availability.

The fraction of groundwater withdrawals \( f_g \) may not be a good indicator for sensitivity to groundwater recharge change in many of the spatial units with \( f_g > 0.5 \) where fossil (non-renewable) groundwater is the major groundwater source. If, in 2055, fossil groundwater would not be a feasible source of water anymore, sensitivity of people that currently use fossil groundwater to changes in GWR could be very high, but may be low otherwise.

The definition of the vulnerability index \( VI \) (equation (1)), including the definition of the sensitivity index with its range of values between 1 and 5, is not based on any empirical or theoretical basis. It rather represents the attempt to express, in a combined manner, both the impact of climate change on the physical system (here: GWR) and the sensitivity of the human system, as these two aspects make up vulnerability.

Figure 5 explores whether a map of \( VI \) (figure 5(b)) provides better information on vulnerability than a map of just GWR decreases (figure 5(a)) or a map that shows the two parts of \( VI \), impact (GWR decrease) and sensitivity (SI), concurrently for each grid cell with different colours (GWR decrease) and intensities (SI) (figure 5(c)). A comparison of \( VI \) (figure 5(b)) and GWR decrease (figure 5(a)) shows that in Europe the ‘high impact/vulnerability’ colours are much less frequent in the \( VI \) map than in the GWR decrease map, which is not true in Africa. This reflects the higher SI of most northern African grid cells (comp. figure 2). The higher SI of most northern African grid cells can also be well recognized by the high intensity colours in figure 5(c). Thus, both map types which include sensitivity provide better information on vulnerability to GWR decrease than a map of just GWR decrease. However, in global-scale maps with a spatial resolution of 0.5°, the two different colour intensities that represent sensitivity cannot be recognized well anymore. Even for the Mediterranean basin, a representation of more than two SI classes by colour intensities is not possible. Metzger et al. (2008) intended to show vulnerability to changes in net carbon storage in Europe due to climate change by representing changes in net carbon storage by a colour range and adaptive capacity by continuously changing colour intensity (their figure 6). However, this endeavour failed, at least in the available electronic file, as the intensities are only distinguishable in the legend but not in the gridded map. Therefore, combining measures of impact and sensitivity into one index like \( VI \) appears to be necessary to show spatially highly-resolved vulnerability.

4.2. Impact of climate change on groundwater resources as compared to other freshwater resources

Groundwater resources should always be considered in relation to the other freshwater resources precipitation and total renewable water resources (total runoff) as these resources are interdependent and not additive. In the context of climate change, it is interesting to compare the changes that the different water resources may undergo. In this comparison, areas with a significant decrease of groundwater resources in a specific scenario are distinguished from areas with a significant increase (table 5). In grid cells with a decrease of more than 10% until the 2050s as compared to 1961–90, average decrease of groundwater recharge is 21–26.8%, depending on the scenario. In these cells, precipitation only decreases by, on average, 12.4–18.5%, while total cell runoff,
Figure 5. Different graphical representations of vulnerability for the example of the Mediterranean region and the ECHAM4 A2 scenario in the 2050s: decrease of GWR (a), vulnerability index VI (b), concurrent presentation of impact (GWR decrease) and sensitivity (SI), where colour intensity increases with increasing sensitivity index SI (c).

Table 5. Different impacts of climate change on GWR, runoff from land, total cell runoff and precipitation, and comparison of climate change impact of GWR to uncertainty of GWR computation related to the equally uncertain precipitation data sets GPCC and CRU (global values).

| Variable | ECHAM4 A2 | HadCM3 A2 | ECHAM4 B2 | HadCM3 B2 | Diff (CRU-GPCC) | Standard dev. of 4 scenarios |
|----------|-----------|-----------|-----------|-----------|-----------------|-----------------------------|
| X < −10% | GWR       | −23.1     | −26.8     | −21.0     | −21.9           | 2.6                         | 0.1 |
|          | TLRb      | −25.7     | −33.4     | −21.6     | −25.9           | 0.1                         | 0.6 |
|          | TCRc      | −29.4     | −38.7     | −25.5     | −30.4           | 0.4                         | 0.6 |
|          | Pd        | −13.8     | −18.5     | −12.4     | −15.0           | 1.3                         | 0.3 |
| −10–10%  | GWR       | −0.1      | −0.2      | 0.1       | 0.1             | 1.9                         | 0.2 |
|          | TLRb      | 5.1       | 2.3       | 5.7       | 2.9             | −1.0                        | 0.4 |
|          | TCRc      | 4.8       | 1.6       | 5.7       | 2.3             | −1.0                        | 0.4 |
|          | Pd        | 4.0       | 1.8       | 4.3       | 1.8             | 0.1                         | 0.4 |
| > 10%    | GWR       | 27.2      | 20.0      | 26.9      | 20.5            | 2.8                         | 0.7 |
|          | TLRb      | 38.5      | 26.6      | 39.1      | 27.0            | 1.2                         | 0.8 |
|          | TCRc      | 41.3      | 28.1      | 41.9      | 29.2            | 1.3                         | 0.8 |
|          | Pd        | 18.7      | 13.2      | 18.3      | 12.9            | 0.3                         | 0.6 |

a Difference between GWR as computed with CRU and GPCC precipitation input for 1961–90, in per cent of GPCC GWR, average over the four scenarios which differ with respect to the grid cells in each of the three change classes.
b Total runoff from land (sum of GWR and fast surface and subsurface runoff).
c Total cell runoff (total runoff from land plus the water balance of surface water bodies, equivalent to total renewable freshwater resources).
d Precipitation.

i.e. total renewable freshwater resources, decrease by 25.5–38.7%. The stronger reaction of total cell runoff as compared to precipitation shows the well-known nonlinearity of runoff generation. It is also due to the concurrent temperature increase that leads to a higher evaporation demand and thus a more than proportional decrease of runoff. Total runoff from land, which does not take into account the water balance of open water bodies, shows a somewhat less strong decrease than total cell runoff, as evapotranspiration from land is restricted by soil water availability (table 5). For grid cells with less than 10% change of GWR or with an increase of more than 10%, the relations are analogous (table 5). Averaged globally, GWR changes by −3.6%/ +0.4% (HadCM3/ECHAM4) in scenario A2 and by −1.4%/ +1.7% in scenario B2, while
total renewable freshwater resources change by $-1.6\% \pm 7.3\%$ in scenario A2, and by $+1.8\% \pm 9.4\%$ in scenario B2. Thus, WGHM predicts a smaller increase or a bigger decrease of global GWR as compared to changes of total renewable water resources.

The uncertainty of computed groundwater recharge that is due to the application of two equally uncertain precipitation data set as input, CRU and GPCC, is small compared to the changes due to climate change until the 2050s (table 5). This is even more pronounced for the other types of freshwater resources (table 5).

4.3. Uncertainty of climate change impacts on groundwater recharge

It is well know that the large differences in precipitation projections that are computed by different global climate models are very likely the major cause for uncertainty of hydrological projections (Bates et al 2008, section 2.3). Figures 1, 3 and 4 and tables 3 and 5 show the discrepant results obtained if the two climate models ECHAM4 and HadCM3 interpret the same greenhouse gas emissions scenario, with Australia being the continent for which the two climate models differ most. Table 5 also shows that the uncertainty of current groundwater recharge estimates that is due to uncertain precipitation observations is much smaller that the uncertainty of groundwater recharge related to the uncertainty of precipitation (and temperature) projections as computed by the two climate models. When considering projected precipitation scenarios of more than 10 global climate models, the models only agree in an increase of precipitation in high northern latitudes and in a decrease in the Mediterranean region (Bates et al. 2008, section 2.3). In most other world regions, less that 80% of the models agree in whether annual precipitation will increase or decrease. The groundwater recharge changes and vulnerabilities that would be computed by using other climate models are therefore likely to look quite different from the results shown in this paper, maybe except for the Mediterranean. Therefore, climate change scenarios cannot be used to quantitatively project the future development of groundwater resources. They should, however, be used to show the large range of possible futures of groundwater resources to which water users might have to adapt. This is true for the macro-scale considered in this paper as well for the assessment of climate change impacts on specific aquifers (e.g. Loaiciga et al 2000, Candela et al. 2009). The low spatial resolution of global climate models of less than 200 km only exacerbates the uncertainty problem in case of the aquifer scale.

5. Conclusions

Calculations with a global hydrological model that is driven by climate change scenarios of two climate models suggest that anthropogenic climate change may have caused, by the 2050s, a decrease of renewable groundwater resources by more than 10% on more than one fifth of the global land area, affecting almost one fifth of the global population of 10.7 billion (IPCC scenario A2, table 3). In case of scenario B2, the percentages of affected area and population decrease by few per cent points only. About 110 million people will be affected by a rather dramatic GWR decrease of more than 70% in A2, and 30–70 million people in B2 (depending on the climate model). One fourth to one third of the world population will have been exposed to an increase of GWR of more than 10% in A2 (one fifth to one third in B2). In many areas, such an increase may require expensive adaptation to elevated groundwater tables. Considering the actual emissions from 1990 to 2005, we currently follow a scenario with higher emissions than in the high emission scenario A2 (Raupach et al 2007). Thus, we might even expect stronger impacts than simulated in this study.

Considering current water scarcity, dependence of water supply on groundwater and societal development, sensitivity of the human system to decreases in GWR shows a strong spatial variability that is nevertheless underestimated in this study. Very high sensitivities are found in India, Pakistan, Iran, Saudi Arabia, Jordan, Morocco and Tunisia, and in eastern China around Beijing. Fortunately, in most of the high sensitivity areas, GWR is not projected to decrease significantly at least until the 2050s, according to the four climate scenarios considered in this study. According to these scenarios, the highest vulnerabilities are found at the North African rim of the Mediterranean Sea, in southwestern Africa, in northeastern Brazil and in the central Andes, which are areas of moderate to high sensitivity. These four regions except northeastern Brazil are also regions where more than 8 out of 12 global climate models agree in a decrease of total water resources for the period 2090–2099, as compared to 1980–1999 (Bates et al 2008, their figure 2.10).

Even though it is informative to present quantitative estimates of societal vulnerability to climate change in addition to climate change impacts on the physical system, I found in this study that such information cannot be easily captured if it is to be provided with a high spatial resolution. If this is the case, vulnerability cannot be presented by showing sensitivities and impacts in spatial units separately as two attributes in the same map because the represented units become too small. It is therefore necessary to combine sensitivity and impact into one vulnerability index in an ad hoc manner, which results in a range of index values that are unfamiliar and thus rather difficult to grasp for the audience. The challenge is to find better ways to present high-resolution vulnerability information to policy-makers and the public.

Finally, vulnerability is mostly considered to be a local phenomenon that is investigated by local-scale studies in which the specific societal (and physical) situation can be taken into account much better than in a global-scale study. Global-scale vulnerability studies, however, allow a consistent comparison of vulnerabilities around the globe and inform decision makers and citizens living in a globalized world. In the future, multi-scale vulnerability assessments should be performed.

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