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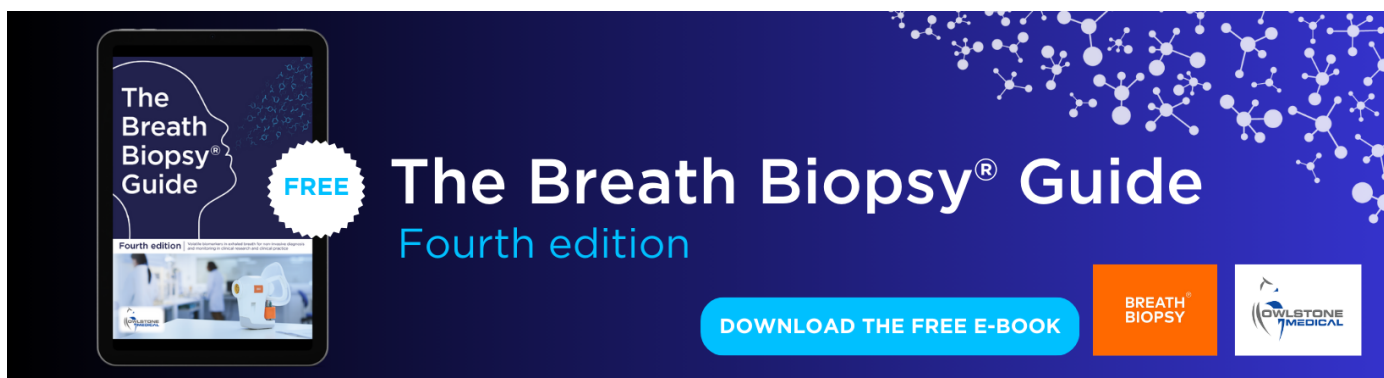
Assessment of transboundary aquifers of the world—vulnerability arising from human water use

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Assessment of transboundary aquifers of the world—vulnerability arising from human water use

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Abstract

Internationally shared, or transboundary, aquifers (TBAs) have long played an important role in sustaining drinking water supply and food production, supporting livelihoods of millions of people worldwide. Rapidly growing populations and their food demands cast significant doubt on the sustainability of TBAs. Here, this study provides a first quantitative assessment of TBAs worldwide with an aquifer stress indicator over the period 1960–2010 using groundwater abstraction, groundwater recharge, and groundwater contribution to environment flow. The results reveal that 8% of TBAs worldwide are currently stressed due to human overexploitation. Over these TBAs the rate of groundwater pumping increased substantially during the past fifty years, which worsened the aquifer stress condition. In addition, many TBAs over Europe, Asia and Africa are not currently stressed, but their aquifer stress has been increasing at an alarming rate (>100%) for the past fifty years, due to the increasing reliance on groundwater abstraction for food production. Groundwater depletion is substantial over several TBAs including the India River Plain (India, Pakistan), the Paleogene and Cretaceous aquifers (the Arabian Peninsula), and a few TBAs over the USA–Mexico border. Improving irrigation efficiency can reduce the amount of groundwater depletion over some TBAs, but it likely aggravates groundwater depletion over TBAs where conjunctive use of surface water and groundwater is prevalent.

Keywords: transboundary aquifers, aquifer stress, groundwater recharge, groundwater abstraction, groundwater depletion, irrigation

 Online supplementary data available from stacks.iop.org/ERL/8/024003/mmedia

1. Introduction

Internationally shared, or transboundary, groundwater resources have long played an important role in sustaining human water needs, e.g. agriculture and other uses, and

natural ecosystems (Bittinger 1972, Margat 1985, Hayton and Utton 1989, Foster and Chilton 2003, Puri and Aureli 2005, Llamas and Martínez-Santos 2005, Ahmad *et al* 2005, Davies *et al* 2013). Yet, they have received significantly less attention compared to transboundary river basins (Puri 2001, Eckstein and Eckstein 2005, Puri and Aureli 2005) that have been extensively studied worldwide since the first compilation of the *Register of International Rivers* in 1978 (United Nations 1978, Wolf *et al* 1999). In 2000, Internationally Shared Aquifer Resources Management (ISARM) was established



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at the 14th Session of the Intergovernmental Council of the International Hydrological Programme of UNESCO. Since then, substantial efforts have been made to identify transboundary aquifer or aquifer systems in various regions, e.g. Africa, Europe, the Americas, and to raise awareness of their societal and environmental importance (Eckstein and Eckstein 2005, Puri and Aureli 2005, Davies *et al* 2013).

Transboundary aquifers (TBAs) traverse international political boundaries, such that groundwater transfers from one country to the others. For instance, most of the groundwater recharge may occur in one country, whereas the groundwater may be extensively abstracted in the other countries. Given the complex nature, TBAs can be classified into different types. Eckstein and Eckstein (2005) defined six different types of TBAs according to the hydrogeological conditions, e.g. physical boundary, (un)confined condition, and hydraulic connectivity with surface water bodies such as river, lakes and wetlands. Davies *et al* (2013) highlighted the importance of socio-economic factors (e.g., water demand, land use, human activities), environmental issues (e.g., sustainability) and institutional elements (e.g., the degree of cooperation, governance capability) together with the hydrological conditions.

Despite the significance, few quantitative assessments of TBA(s) are present. Cobbing *et al* (2008) analyzed the groundwater resources availability and the corresponding water demand over a few TBAs shared by South Africa and the neighboring countries. Regional studies by Rodell *et al* (2009) and Tiwari *et al* (2009), using the Gravity Recovery and Climate Experiment (GRACE), revealed a considerable amount of groundwater depletion, i.e. the persistent removal of groundwater from aquifer storage owing to groundwater abstraction in excess of groundwater recharge, from the aquifer underlying India, Pakistan, and Bangladesh, most of which is used for irrigation for food production. A recent study by Gleeson *et al* (2012) calculated the groundwater footprint, i.e. the area required to sustain groundwater abstraction and groundwater-dependent ecosystem services, for major groundwater basins (BGR/UNESCO 2008). These studies suggest that some TBAs are under substantial stress, yet no comprehensive overview of aquifer stress of global TBAs is available.

Here, a first quantitative assessment of TBAs is provided worldwide with an aquifer stress indicator over the period 1960–2010 that extends beyond most global analyses. The aquifer stress indicator (AQSI) is calculated with groundwater abstraction (GW_A), natural groundwater recharge (R_{Nat}), and additional recharge from irrigation as return flow (R_{Irr}). In addition, groundwater contribution to environment flow (R_{Env}) is incorporated. In many regions, groundwater provides a reliable source of water to environment, such as baseflow in streamflow. This term, thus, encompasses the broad meaning of environmental significance of groundwater recharge, not only sustaining groundwater-dependent ecosystems in streamflow, wetlands, springs, and marine environments, but also contributing to evapotranspiration from vegetation, e.g. forest. The AQSI is defined as $GW_A / [(R_{Nat} + R_{Irr}) - R_{Env}]$ (all in volume per time such as $km^3 yr^{-1}$) that essentially

expresses how much fraction of the available groundwater recharge is used for human water use. The AQSI used a similar concept as groundwater footprint (GF) developed by Gleeson *et al* (2012), but it is expressed as a dimensionless unit rather than area (A_A ; m^2), thus equals to GF/A_A . The AQSI above 1 is possible at the expense of groundwater contribution to environmental flow and groundwater mining or groundwater depletion. It should be noted that to estimate the amount of groundwater depletion, the difference between abstraction and recharge or $GW_A - (R_{Nat} + R_{Irr})$ is used, which approximately expresses the change in aquifer storage. The fluxes over each TBA is aggregated to calculate the AQSI and the amount of groundwater depletion, integrating lateral groundwater flow that may naturally occur due to the difference in groundwater heads and might occur due to groundwater pumping. In this study, the term ‘aquifer’ refers solely to groundwater resources and the term ‘TBAs’ refer to groundwater resources that traverse international political boundaries among multiple countries.

In section 2, the data, model and methods used are described. The results are presented in section 3 and in section 4 the discussion is presented and the conclusions are drawn.

2. Data, model and methods

2.1. Transboundary Aquifers of the World

A global inventory of TBAs was obtained from Transboundary Aquifers of the World—Update 2012 (www.un-igrac.org/publications/456/) compiled by the International Groundwater Resources Assessment Centre (IGRAC; www.un-igrac.org/). Transboundary Aquifers of the World—Update 2012 provides, to our knowledge, the first spatially explicit and the most comprehensive information on TBAs worldwide. At present, it identifies 445 TBAs and delineates aquifer boundaries. The number of TBAs was 380 in 2009 (Transboundary Aquifers of the World 2009; www.un-igrac.org/publications/323/), but substantially increased as a result of various international efforts identifying TBAs. It should be noted that in the TBA polygons obtained from the IGRAC, some small TBAs are being merged and the number of TBAs totals 408. The IGRAC brings together regional and continental information of TBAs provided by various institutions, e.g. BGR/WHYMAP (www.whymap.org/), UNESCO (www.unesco.org/), UNECE (www.unece.org/), and ISARM (www.isarm.org/). The aquifer boundaries of the TBAs remain as close as the original sources provided by these institutions. In case the exact aquifer boundaries are not known, rough boundaries with the highest level of certainty are delineated highlighting their approximate extent. The boundaries are not properly delineated for some TBAs, e.g. in Asia and Africa, and ongoing efforts are underway to further identify TBAs and delineate their proper boundaries. Figure 1 shows the 408 TBAs with the aquifer boundaries delineated.

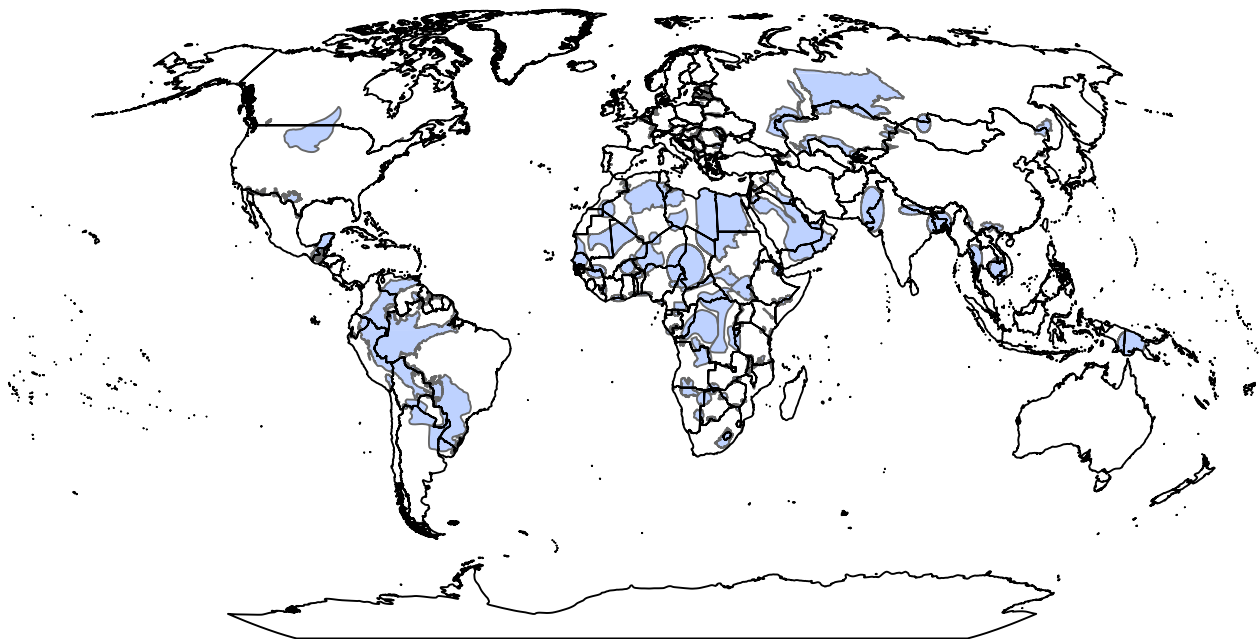


Figure 1. Transboundary aquifers (TBAs) of the world (source: International Groundwater Resources Assessment Centre; www.un-igrac.org/publications/456).

2.2. Global groundwater abstraction

Country groundwater abstraction rates for 2000 were obtained from the IGRAC GGIS data base (www.un-igrac.org/publications/104). Since the IGRAC GGIS data base has missing values for some countries (e.g., Afghanistan, several African countries), additional country groundwater abstraction rates for 15 countries were obtained from the WRI EarthTrends (www.wri.org/project/earthtrends/), Foster and Loucks (2006), and Shah (2005). The country groundwater abstraction rates change in proportion to country total water demand over the years (Wada *et al* 2010). The country groundwater abstraction rates were then distributed to 0.5° grid cells, i.e. 50 km at the Equator, where surface water availability, i.e. water in rivers, lakes, reservoirs, and wetlands, is insufficient to meet the total water demand, i.e. water demand in excess of surface water availability, as the main locations where groundwater is abstracted to satisfy the deficiency over countries (Wada *et al* 2012).

2.3. Total water demand and surface water availability

The total water demand was calculated at a 0.5° global grid for agricultural (livestock and irrigation), industrial and domestic sectors using the latest available data on socio-economic (e.g., population and Gross Domestic Product), technological (e.g., energy and household consumption and electricity production) and agricultural (e.g., the number of livestock, irrigated areas and irrigation efficiency) drivers. We refer to Wada *et al* (2011a, 2011b) for the detailed methodologies. The surface water availability was simulated using the global hydrological and water resources model PCR-GLOBWB (Wada *et al* 2010, Van Beek *et al* 2011). PCR-GLOBWB calculates for each grid cell ($0.5^\circ \times 0.5^\circ$ globally) and for

each time step (daily) the water storage in two vertically stacked soil layers and an underlying groundwater layer, as well as the water exchange between the layers and between the top layer and the atmosphere (rainfall, evapotranspiration and snow melt). Sub-grid variability is taken into account by considering separately tall and short vegetation, open water (lakes, reservoirs, floodplains and wetlands), different soil types (FAO Digital Soil Map of the World), and the area fraction of saturated soil calculated by Improved ARNO scheme (Hagemann and Gates 2003) as well as the frequency distribution of groundwater depth based on the surface elevations of the 1×1 km Hydro1k data set. The third groundwater layer represents the deeper part of the soil that is exempt from any direct influence of vegetation and constitutes a groundwater reservoir fed by active recharge, and is explicitly parameterized and represented with a linear reservoir model (Kraaijenhoff van de Leur 1958). The model includes surface water routing considering storage in rivers, lakes, reservoirs and wetlands. The model was forced with daily fields of precipitation, temperature, and reference (potential) evapotranspiration. For the period 1960–2000, precipitation and temperature were prescribed by the CRU TS 2.1 monthly data set (Mitchell and Jones 2005), which was subsequently downscaled to daily fields by using the ERA40 re-analysis data (Uppala *et al* 2005, Kållberg *et al* 2005). The precipitation data was corrected for snow undercatch bias over the Northern Hemisphere (Adam and Lettenmaier 2003). The prescribed reference evapotranspiration was calculated based on the Penman–Monteith equation according to the FAO guidelines (Allen *et al* 1998) using the time series data of CRU TS 2.1 with additional inputs of radiation and wind speed from the CRU CLIM 1.0 climatology data set (New *et al* 2002). This was subsequently downscaled to daily fields on the basis of the daily temperature from the ERA-40 re-analysis

data. To extend our analysis to the year 2010, the model was forced by a comparable daily climate fields taken from the ERA-Interim re-analysis data (Dee *et al* 2011). Daily fields of GPCP-corrected precipitation and temperature (GPCP: Global Precipitation Climatology Project; www.gewex.org/gpcp.html) were obtained, and reference evapotranspiration was calculated by the same method retrieving relevant climate fields from the ERA-Interim climate dataset. For compatibility with our overall analysis, this climate dataset, i.e. precipitation, reference evapotranspiration, and temperature, was bias-corrected by scaling the long-term monthly means of these fields to those of the CRU TS 2.1 data set, wherever station coverage by the CRU is adequate. Otherwise the original ERA-Interim data were returned by default. The calculated water demand and simulated surface water availability have been extensively validated in earlier work (Van Beek *et al* 2011, Wada *et al* 2011a, 2012).

2.4. Natural, artificial, and environmental groundwater recharge

Natural groundwater recharge, additional recharge from irrigation as return flow, and groundwater contribution to environmental flow were simulated using the PCR-GLOBWB at a 0.5° spatial resolution and at a daily time step. Natural groundwater recharge is simulated as the net flux from the lowest soil layer to the groundwater layer, i.e. deep percolation minus capillary rise. Note that simulated natural groundwater recharge is not reconciled to local observations and underlying geology. However, recharge interacts with groundwater storage as it can be balanced by capillary rise if the top of the groundwater level is within 5 m of the topographical surface (calculated as the height of the groundwater storage over the storage coefficient on top of the streambed elevation and the sub-grid distribution of elevation). Groundwater storage is fed by the recharge but drains by a reservoir coefficient that includes information on lithology and topography (e.g., hydraulic conductivity of the subsoil). The ensuing capillary rise is calculated as the upward moisture flux that can be sustained when an upward gradient exists and the moisture content of the soil is below field capacity. Also, it cannot exceed the available storage in the underlying groundwater reservoir. Additional recharge from irrigation is formulated from the fact that in irrigation practice water is supplied to wet the soil to field capacity during the application and the amount of irrigation water in excess of the field capacity can percolate to the groundwater system (Wada *et al* 2012). The additional recharge rate thus equals the unsaturated hydraulic conductivity of the deeper soil layer at field capacity, assuming gravitational drainage. However, the total percolation losses are further constrained by the reported country-specific loss factor based on Rohwer *et al* (2007). Groundwater contribution to environmental flow, being an important component during low flow conditions (Smakhtin 2001, Smakhtin *et al* 2004), was estimated using the fraction of Q_{90} , i.e. the monthly streamflow that is exceeded 90% of the time, to Q_{Avg} or the long-term average streamflow at the basin scale conforming to Gleeson *et al* (2012).

2.5. Uncertainty assessment

An uncertainty analysis of groundwater abstraction and groundwater recharge was performed according to Wada *et al* (2010). In brief, the uncertainty was identified by comparing the country-based abstraction rates used in this study to alternative sources such as those reported in the FAO AQUASTAT data base (www.fao.org/nr/water/aquastat/main/index.stm). Given the highly uncertain nature, a conservative approach was chosen by attributing the difference between the two sources completely to our data. We identified an uncertainty model for groundwater recharge by comparing the PCR-GLOBWB recharge estimate with an independent estimate (Döll and Fiedler 2008) and the PCR-GLOBWB streamflow estimates with the GRDC observed streamflow data (www.bafg.de/cln_031/nn_293894/GRDC/). Using these uncertainty models we performed a Monte-Carlo simulation, generating 100 equiprobable realizations of groundwater abstraction and 100 equiprobable realizations of groundwater recharge, thus resulting in 10,000 possible realizations of AQSI and groundwater depletion (assuming errors in groundwater recharge and groundwater abstraction to be independent). From these, the mean and the standard deviations of groundwater abstraction, groundwater recharge, AQSI, and groundwater depletion were estimated for each TBA.

3. Results

3.1. Aquifer stress and the trends over the period 1960–2010

Figure 2 shows calculated aquifer stress for each TBA and the increase in per cent between 1960 and 2010 (see also table 1 for the aquifer characteristics for stressed TBAs). Overexploited TBAs locate primarily over (semi-)arid or intense irrigated regions including India, Pakistan, Central Asia, the Arabian Peninsula, the southern USA, and northern Mexico. In these regions, groundwater pumping exceeds the rate of groundwater recharge ($AQSI \geq 1$), which indicates groundwater mining primarily for irrigation. Declining groundwater levels or groundwater depletion have also been reported over these regions in recent literature (Konikow and Kendy 2005, Karami and Hayati 2005, Shah 2005, Foster and Loucks 2006, Rodell *et al* 2009, Tiwari *et al* 2009, Konikow 2011). Over the last 50 years, the aquifer stress substantially increased for these presently stressed TBAs. For example, the aquifer stress of a few TBAs over the USA–Mexico borders increased by 41–114% primarily due to expansion of irrigated areas. Over the India River Plain (India, Pakistan), regardless of a large expansion of irrigated areas, and sharp rise in population and their drinking water requirements, the aquifer stress increased by only 48% due to substantial contribution of additional recharge or return flow from surface water irrigation, which cancelled out increased groundwater abstraction for irrigation. However, the amount of groundwater depletion increased substantially over the India River Plain for the last 50 years (see section 3.2). Over the Paleogene and Cretaceous aquifers

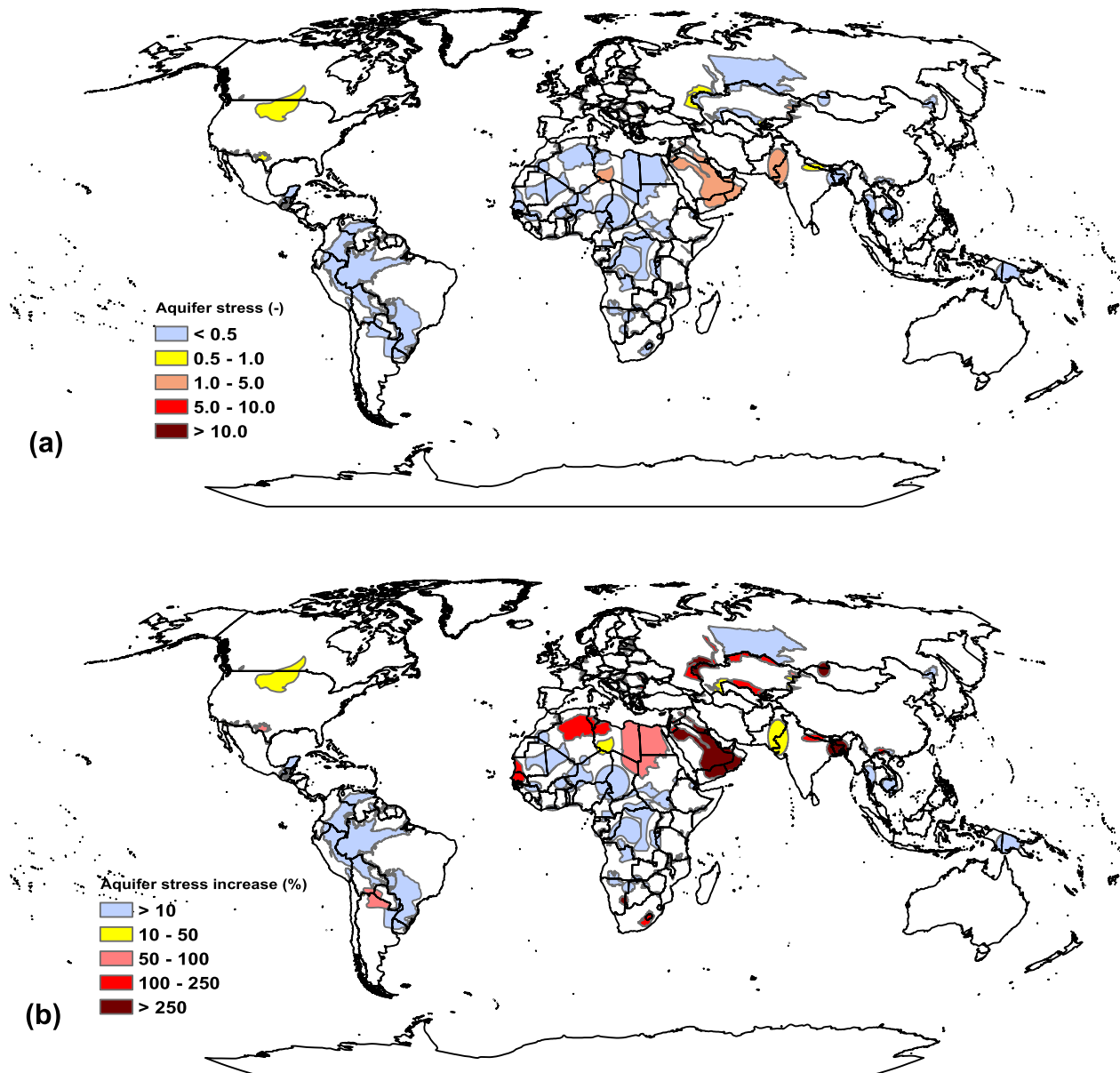


Figure 2. (a) Aquifer stress (AQSI; dimensionless) for each TBA and (b) the increase of aquifer stress (per cent) between 1960 and 2010.

(the Arabian Peninsula) where irrigation is sustained by non-renewable groundwater, i.e. groundwater resources that are not replenished, (Foster and Loucks 2006, Wada *et al* 2012), large increases in irrigation water use exacerbated the aquifer stress by more than 392%. The same holds for the Mourzouk (Algeria, Libya, Niger) and the Puneños (Argentina, Bolivia) where precipitation is extremely low and almost no groundwater recharge occurs from the precipitation. It should be noted that many of currently non-stressed TBAs with $0.1 \leq \text{AQSI} < 1.0$ have also experienced substantial increase in aquifer stress. The aquifer stress increased by more than 250% for many TBAs over eastern Europe, Central Asia, northern Africa, and southern South America due to a rapidly growing population and their food demand met by increased irrigation (see supplementary material available at stacks.iop.org/ERL/8/024003/mmedia for aquifer stress of all TBAs).

3.2. Groundwater depletion

Groundwater use is highly unsustainable over some of the major TBAs due to human overexploitation (see table 1). To reduce the aquifer overdraft to the sustainable rate, the groundwater abstraction has to fall substantially over these TBAs. For example, over the India River Plain (India, Pakistan) about $11.7 \pm 3.6 \text{ km}^3 \text{ yr}^{-1}$ or about 20% of the groundwater abstraction needs to be reduced or supplied from other water resources, e.g. the Indus, aqueducts. However, given the fact that surface water resources are very scarce in the region, it is not realistic to withdraw more surface water unless additional reservoirs are constructed to store more water and release it during the growing season of irrigated crops. This amount equals nearly 10% of the irrigation water demand over the aquifer. For the Paleogene and Cretaceous aquifers (the Arabian Peninsula), withdrawing

Table 1. Aquifer characteristics for stressed TBAs.

TBA	Country	Area ^a (million km ²)	Population ^b (millions)	Water demand ^c (irr.; km ³ yr ⁻¹)	GW Depletion ^c (km ³ yr ⁻¹)	AQSI ^c (increase; %)	Recharge per capita $R_{\text{Nat}} (R_{\text{Nat}} + R_{\text{Irr}})^d$ (m ³ capita ⁻¹ yr ⁻¹)
Paleogene and Cretaceous aquifers	Iraq, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Syria, UAE, Yemen, Bahrain	2.1	30.0	24.2 (21.8)	12.0 ± 3.2	3.5 ± 0.84 (392%)	233.2 (304.4)
India River Plain	India, Pakistan	0.77	173.2	143.3 (135.4)	11.7 ± 3.6	1.3 ± 0.4 (48%)	63.5 (265.0)
Mourzouk	Algeria, Libya, Niger	0.29	0.31	0.5 (0.4)	0.4 ± 0.1	4.7 ± 1.5 (49%)	70.2 (266.9)
Tacheng Basin/Alakol	China, Kazakhstan	0.05	0.62	3.4 (3.2)	0.8 ± 0.3	3.1 ± 0.9 (27%)	251.3 (1351.8)
Sonoyta-Pápagos	Mexico, USA	0.02	0.08	0.6 (0.6)	0.5 ± 0.2	33.1 ± 11.8 (114%)	9.2 (198.8)
Cuenca Baja del Río Colorado	Mexico, USA	0.02	1.8	4.9 (4.4)	3.4 ± 0.8	5.0 ± 1.8 (41%)	26.1 (500.1)
Puneños	Argentina, Bolivia	0.02	0.07	0.06 (0.04)	0.05 ± 0.02	6.1 ± 2.3 (40%)	14.5 (41.3)
Dobrudja	Bulgaria, Romania	0.01	0.21	5.1 (2.0)	0.8 ± 0.3	2.4 ± 0.7 (279%)	750.7 (821.2)
Neogene-Sarmatian aquifer							
Bolsón del Hueco-Valle de Juárez	Mexico, USA	0.01	2.2	1.5 (0.6)	0.2 ± 0.07	4.0 ± 1.8 (65%)	2.0 (32.5)
Ollague-Chiguana	Bolivia, Chile	0.006	0.006	0.03 (0.02)	0.01 ± 0.004	3.6 ± 1.1 (121%)	13.8 (26.5)

^a Area is obtained from the Transboundary Aquifers of the World—Update 2012.

^b Population numbers were estimated from the FAOSTAT (<http://faostat.fao.org/>) and Klein Goldewijk and van Drecht (2006).

^c Water demand, groundwater depletion, and AQSI were taken from the results of this study. Values for the year 2010 are provided.

^d Recharge per capita were taken from the results of this study. Values for the long-term average 1960–2010 are provided.

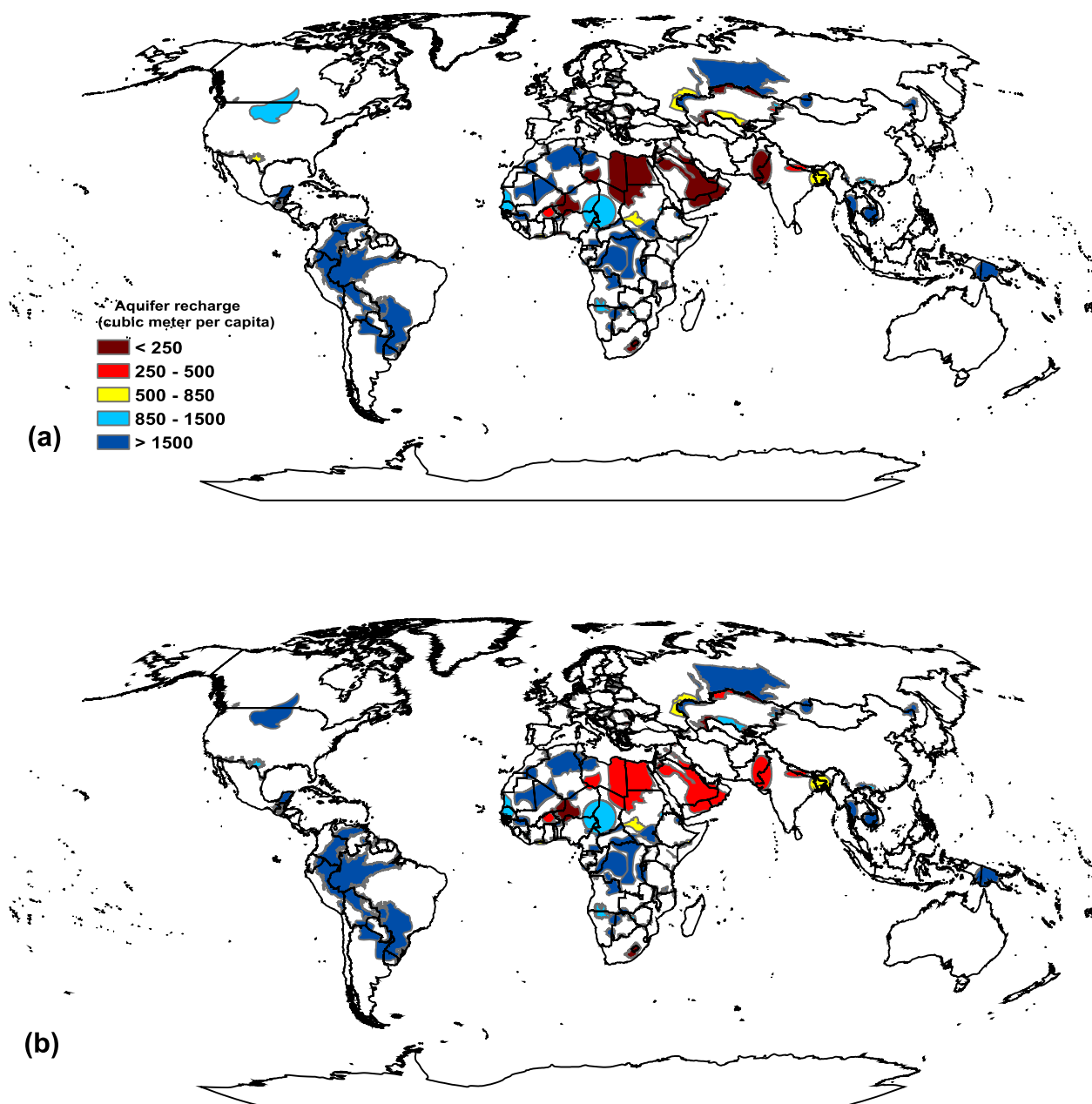


Figure 3. Long-term average (1960–2010) groundwater recharge per capita ($\text{m}^3 \text{ capita}^{-1} \text{ yr}^{-1}$) based on (a) natural groundwater recharge and (b) natural groundwater recharge with additional recharge from irrigation over each TBA.

more surface water resources are not physically feasible due to arid climate and extremely low precipitation. Groundwater is the predominant water resource to sustain the large irrigation water demand for food production over the region ($21.8 \text{ km}^3 \text{ yr}^{-1}$). Groundwater depletion amounts $12.0 \pm 3.2 \text{ km}^3 \text{ yr}^{-1}$ and nearly half of the water demand over the aquifer. Groundwater depletion also amounts more than half of the water demand for the Cuenca Baja del Río Colorado and the Sonoyta–Pápagos over the USA–Mexico border.

3.3. Groundwater recharge per capita

Figure 3 shows over each TBA a long-term mean groundwater recharge per capita. Per capita recharge is extremely low

(<250 m^3) for several TBAs notably over India and Pakistan, the Central Asia, the Middle East and North Africa and the USA and Mexico. Since only groundwater recharge is considered here, it is not directly comparable, but it is worth mentioning that annual total renewable water resources (blue water) below 500 $\text{m}^3 \text{ capita}^{-1}$ is considered as absolute water scarcity (Rijsberman 2006). Some TBAs have a per capita recharge lower than 50 m^3 , for example the Puneños (Argentina, Bolivia) and the Bolsón del Hueco–Valle de Juárez (USA, Mexico). These TBAs receive low precipitation, most of which evapotranspires before percolating to the water table. The Lower Ganges receives much higher precipitation, yet the per capita recharge is low ($\approx 500 \text{ m}^3$) due to a large population size. When including additional recharge

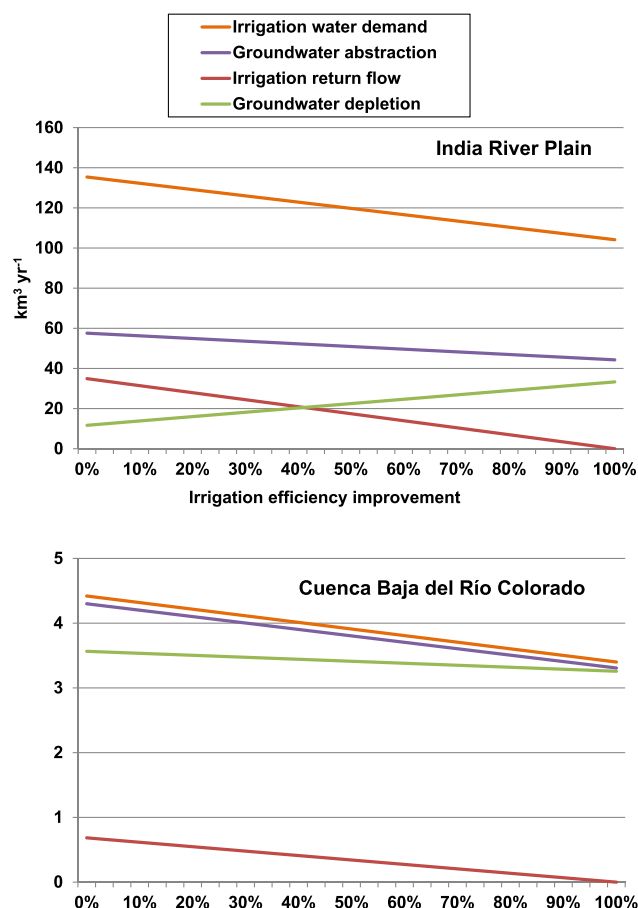


Figure 4. The relationship among improved irrigation efficiency, irrigation water demand, groundwater abstraction, irrigation return flow and groundwater depletion for the India River Plain (India, Pakistan), and the Cuenca Baja del Río Colorado (USA, Mexico).

from irrigation, per capita recharge increases substantially over a few TBAs. Return flow from surface water irrigation increases recharge over India and Pakistan, Central Asia, and the USA and Mexico (Döll *et al* 2012), whereas increase in recharge is predominantly induced from mining groundwater over the Middle East and North Africa.

3.4. Groundwater depletion and irrigation efficiency

Figure 4 shows approximately the relationship among improved irrigation efficiency, irrigation water demand, groundwater abstraction, irrigation return flow and groundwater depletion for the selected TBAs. The irrigation efficiency taken from Rohwer *et al* (2007) (see section 2.3) was adjusted, and all the amounts, i.e. irrigation water demand, groundwater abstraction, irrigation return flow, groundwater depletion, were recalculated. For example, the irrigation efficiency improvement of 0% indicates that the irrigation efficiency remains as reported in Rohwer *et al* (2007), whereas that of 100% indicates the condition in which irrigation water supply equals irrigation water demand, or no losses during the irrigation water application. For the Cuenca Baja del Río Colorado (USA, Mexico), improving irrigation efficiency can reduce the amount of groundwater depletion due to the

fact that the farmers predominantly rely on groundwater resources for irrigation. For instance, improving irrigation efficiency by 30% can decrease 5% of groundwater depletion for these aquifers. The same holds for the Paleogene and Cretaceous aquifers (the Arabian Peninsula). However, for the India River Plain (India, Pakistan) where conjunctive water use of surface water and groundwater is prevalent to meet crop demand, improving irrigation efficiency does not necessarily decrease the amount of groundwater depletion such that it also reduces additional recharge from surface water irrigation or return flow to groundwater. As shown in figure 4 the relationship among improved irrigation efficiency and groundwater depletion exhibits a very different trend for the India River Plain compared to that of the Cuenca Baja del Río Colorado. The irrigation water demand and groundwater abstraction decreases as the irrigation efficiency improves. However, the groundwater depletion increases as the irrigation return flow decreases more rapidly than decrease in abstraction as a result of improved irrigation efficiency.

3.5. Country share of groundwater abstraction and recharge for stressed TBAs

Figure 5 shows the proportion of groundwater abstraction and groundwater recharge of countries sharing stressed TBAs. For the India River Plain (India, Pakistan), the country share of groundwater abstraction and groundwater recharge is rather homogeneous, for which about a quarter of groundwater abstraction and groundwater recharge comes from India, whereas the three-fourth attributes to Pakistan. However, the proportion of groundwater abstraction and groundwater recharge among countries is heterogeneous over other TBAs. For instance, over the Tacheng Basin/Alakol (China, Kazakhstan) almost all groundwater abstraction attributes to China, whereas nearly half of groundwater recharge comes from Kazakhstan. For the TBAs over the USA–Mexico borders, most of groundwater abstraction occurs within the USA, except the Bolsón del Hueco–Valle de Juárez where the USA and Mexico abstract the similar amount of groundwater. Over these TBAs, groundwater pumping is much faster than the rate of groundwater recharge, which indicates a substantial amount of groundwater mining and decreasing groundwater storage.

4. Discussion and conclusions

This study provides a first comprehensive and quantitative assessment of aquifer stress of TBAs worldwide. The results reveal that 31 TBAs or 8% of the TBAs are currently stressed due to human overexploitation. Groundwater depletion is substantial over several TBAs including the India River Plain (India, Pakistan), the Paleogene and Cretaceous aquifers (the Arabian Peninsula), and a few TBAs over the USA–Mexico border. Fossil groundwater, not being an active part of the current hydrological cycle, is used as an additional, albeit non-renewable, source of major irrigation water. Over these TBAs the rate of groundwater pumping increased substantially during the past 50 years, primarily due to

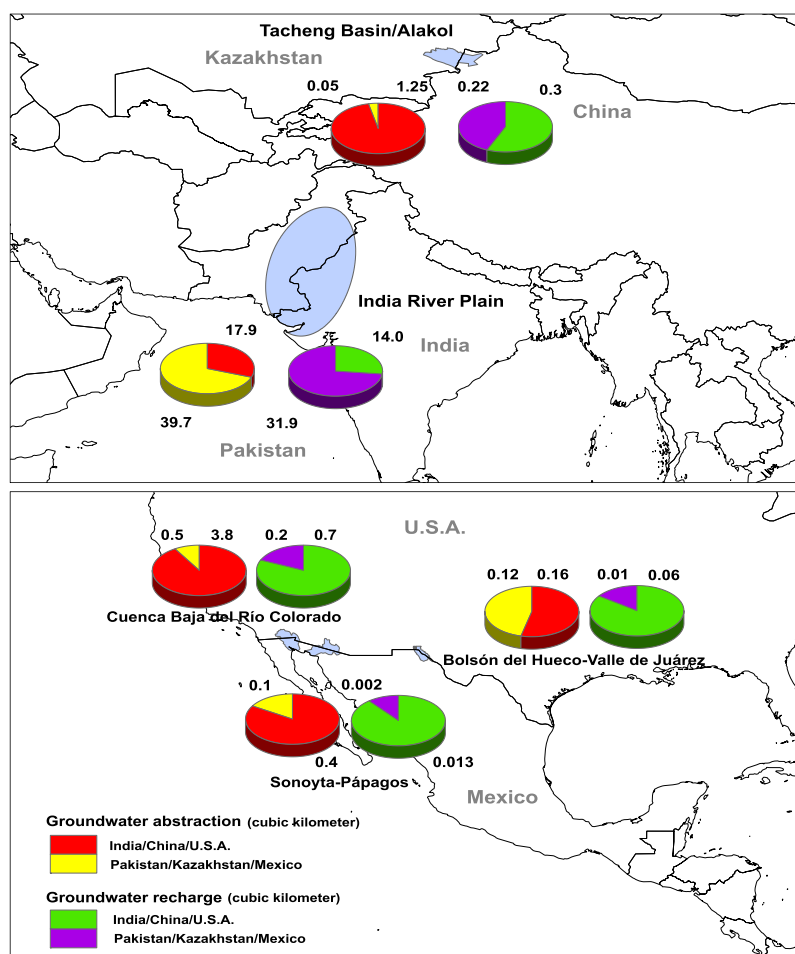


Figure 5. The country share of groundwater abstraction and groundwater recharge ($\text{km}^3 \text{yr}^{-1}$) for 2010 over the selected stressed TBAs.

the expansion of irrigated areas and the increased standard of living, which worsened the aquifer stress condition by 27%–392%. In addition, many TBAs over Europe, Asia and Africa are not currently stressed ($0.1 \leq \text{AQSI} < 1.0$ in 2010), but their aquifer stress has been increasing at an alarming rate ($>100\%$) for the past 50 years, due to the increasing reliance on groundwater abstraction for food production. Further increase in groundwater abstraction likely aggravates the aquifer stress conditions ($\text{AQSI} \geq 1$) for many of those TBAs. Human exploitation likely has a larger impact on the sustainability of these TBAs compared to anticipating climate change that has little influence on groundwater recharge over these regions (Döll 2009).

The AQSI used in this study is a simple and first-order approximation to depict the consequences of human water use over TBAs. This indicator is well suited for shared aquifers that physically transgress international political boundaries but is not easily applicable to different types of shared aquifers: (1) an aquifer that is within the territory of one country but is hydraulically connected to surface water bodies that are transboundary (e.g., transboundary river basins), and (2) a confined aquifer that traverses international political boundaries with the recharge zone in another country (Eckstein and Eckstein 2003, 2005). Such shared aquifers need careful attention that requires a comprehensive

assessment of surface water and groundwater resources, and their use considering substantial internal heterogeneity within a shared aquifer or transboundary water bodies. Furthermore, the indicator addresses the sustainability from the water quantity point of view, but does not account for water quality issues such as groundwater contamination that affects the amount of readily available groundwater in the aquifer. Therefore, the assessment presented here may be considered as the lower end of aquifer stress.

Although the uncertainty assessment was performed, groundwater abstraction is highly uncertain (Ahmad *et al* 2005). Several global estimates exist for the present condition, varying between 545 and 1100 $\text{km}^3 \text{yr}^{-1}$ (Zektser and Everett 2004, Shah 2005, Döll 2009, Siebert *et al* 2010). Siebert *et al* (2010) quantified the amount of groundwater consumed through current irrigation practice to be 545 $\text{km}^3 \text{yr}^{-1}$. Döll (2009) used a global hydrological model and subnational statistics of a fraction of groundwater to total water use to calculate groundwater abstraction to be 1100 $\text{km}^3 \text{yr}^{-1}$. Our estimate ($\sim 800 \pm 150 \text{ km}^3 \text{yr}^{-1}$) obtained from the IGRAC GGIS database lies in the middle among these estimates. As a limited validation exercise, we compared our groundwater abstraction estimate to available reported estimates over subnational units of a few major groundwater users, India, USA, China and Mexico (see figure 6). The comparison

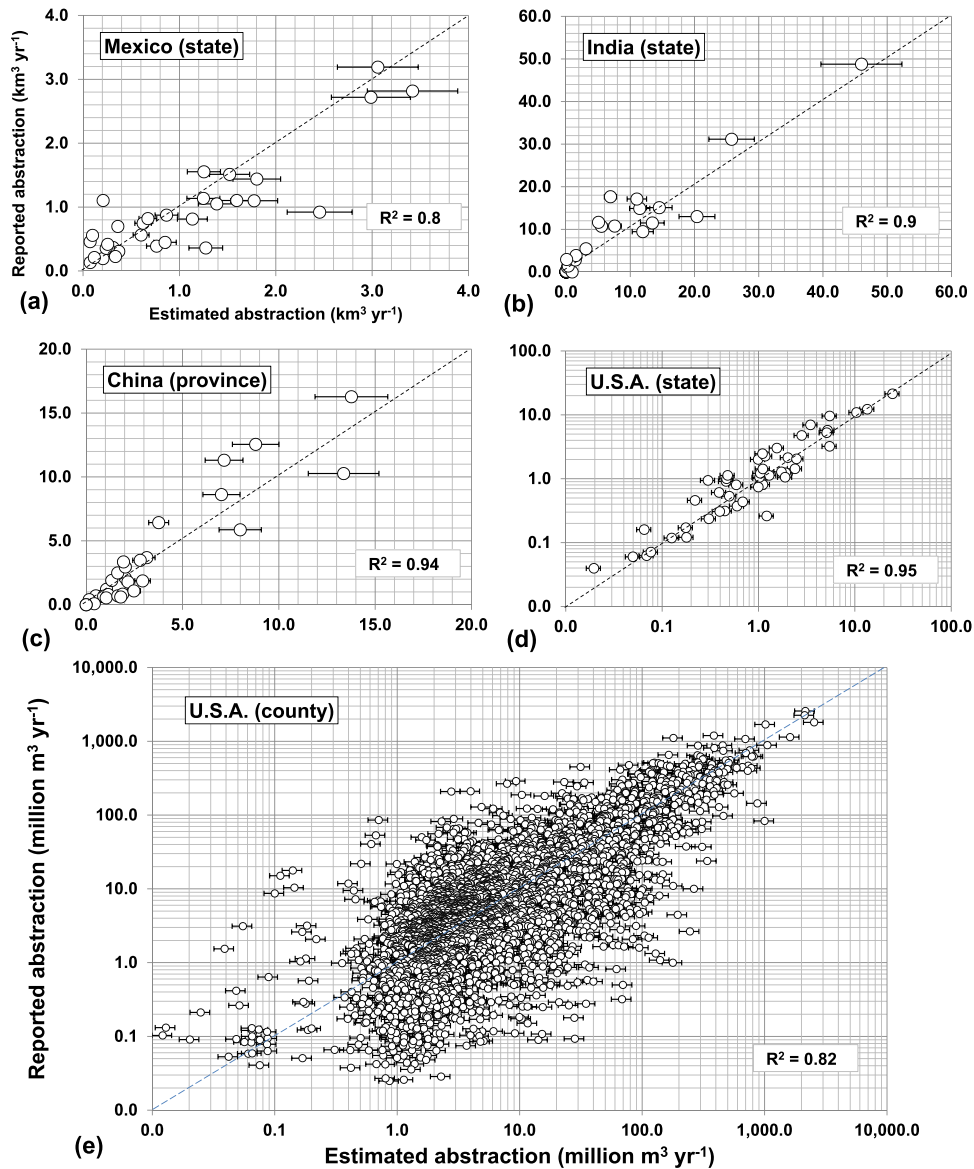


Figure 6. Comparison of reported (y-coordinate) and estimated groundwater abstraction (x-coordinate) for (a) Mexico per state ($N = 32$), (b) India per state ($N = 35$), (c) China per province ($N = 30$), (d) conterminous USA per state ($N = 48$) in log-log plots, and (e) conterminous USA per county ($N = 2751$) in log-log plots. All abstractions are given in $\text{km}^3 \text{ yr}^{-1}$ except the conterminous USA per county given in million $\text{m}^3 \text{ yr}^{-1}$. Estimated groundwater abstraction at 0.5° was spatially aggregated to county, and state or provincial level if applicable. Error bars show standard deviation (σ) for each state or province and county from the uncertainty assessment. R^2 denotes the coefficient of determination. The dashed lines represent the 1:1 line. The reported groundwater abstraction was obtained from the CONAGUA (Statistics on Water in Mexico; www.conagua.gob.mx/english07/publications/Statistics_Water_Mexico_2008.pdf) for Mexico, from the Central Ground Water Board (www.cgwb.gov.in/) for India, from the Ministry of Environmental Protection (Freshwater Environment; http://english.mep.gov.cn/standards_reports/EnvironmentalStatistics/yearbook2006/200712/t20071218_115211.htm) for China, and from the US Geological Survey (Water Use in the United States; <http://water.usgs.gov/watuse/>).

generally show good agreement for these countries with R^2 (the coefficient of determination) ranging from 0.8 to 0.95 (p -value < 0.001). We slightly overestimated the groundwater abstraction for Mexico and the USA (slope ≈ 0.85 – 0.98), particularly for the central Mexico and the western USA. In contrast, we slightly underestimated the groundwater abstraction for India and China (slope ≈ 1.03 – 1.05), but the deviations between the reported and estimated abstraction are rather small and mostly within the uncertainty range.

Groundwater recharge is difficult to estimate and is also subject to large uncertainties, particularly in

(semi-)arid environment where annual average potential evapotranspiration exceeds annual average rainfall, and groundwater recharge is often restricted to episodic rainfall events (Crosbie *et al* 2012). As it is rarely observed directly, especially at the scale at which it is modeled in this study, we assessed its uncertainty by comparing two independent sources including our estimate. Our simulated long-term average global groundwater recharge flux (1960–2010) including additional recharge from irrigation amounts to $\sim 17.0 \cdot 10^3 \pm \sim 5.0 \cdot 10^3 \text{ km}^3 \text{ yr}^{-1}$ ($\sim 40 \pm \sim 10\%$ of our simulated total runoff). Our estimate is about 30% larger than

that of Döll and Fiedler (2008) who estimated the long-term average global groundwater recharge to be $12.7 \cdot 10^3 \text{ km}^3 \text{ yr}^{-1}$ ($\sim 35\%$ of their simulated total runoff). The difference is partly attributed to the fact that Döll and Fiedler (2008) did not account additional recharge from irrigation. Although the difference may be large, when accounting the uncertainty of groundwater recharge, a conservative approach was adopted attributing the difference between the two estimates fully to our estimate (as opposed to viewing the two model results as two independent samples of the true but unknown groundwater recharge), which contains errors in the model structure and climate forcing from the two estimates.

Furthermore, additional recharge from irrigation (R_{Irr}) and groundwater contribution to environment flow (R_{Env}) are currently estimated with a simplistic approach. R_{Irr} equals the amount of water surplus from the soils in irrigated areas and represents potential recharge fluxes to aquifers, taking into account time lags and natural flow processes that may take years to decades when the water actually reaches to the groundwater system as groundwater recharge (Scanlon *et al* 2010, Taylor *et al* 2013). Therefore, the calculated AQSI may be somewhat overestimated for TBAs with a deep aquifer system with additional porosity, providing the necessary storage to create the longer recession period (Scanlon *et al* 2010). R_{Env} sustains ecosystems in many places, and can be a major factor determining the distribution of ecosystem types over the regions. However, not all groundwater-dependent ecosystems rely on groundwater directly and not all are solely reliant on groundwater. The degree and nature of their dependency on groundwater is valuable information to define the amount of R_{Env} . Such information is, however, rarely available, but this term requires further consideration that needs to be constrained by available local information. Increasing aquifer stress pose a serious threat to groundwater-dependent ecosystems, but further efforts are needed to more realistically quantify the amount of R_{Env} , which improves our understanding how groundwater-dependent ecosystems should be managed.

Our results highlight the increasing reliance of irrigation on groundwater resources over many TBAs with time. The increase is attributable to the rapid expansion of irrigated areas during the past 50 years (Wisser *et al* 2010) and fast population growth. Scarce surface water resources and drought conditions worsen the sustainability of groundwater resources (Famiglietti *et al* 2011, Scanlon *et al* 2012a, 2012b, Aeschbach-Hertig and Gleeson 2012) particularly for TBAs in (semi-)arid regions (Gleick 2010). Groundwater abstraction may be reduced by withdrawing additional surface water, however, surface water is very scarce in the regions where most stressed TBAs are present. Improving irrigation efficiency can increase water productivity, i.e. amount of crop yield per volume of water supplied (e.g., kg m^3 or $\text{kg ha}^{-1} \text{ mm}^{-1}$), and reduces the amount of water supplied for irrigation (Passioura 2006, Perry *et al* 2009, Gleick *et al* 2010, Perry 2011). In fact, over water scarce regions where irrigation predominantly relies on groundwater, improving irrigation efficiency can reduce groundwater abstraction for irrigation decreasing the aquifer stress (AQSI). However, in

regions where conjunctive water use of surface water and groundwater is prevalent for irrigation, improving irrigation efficiency does not necessarily decrease the aquifer stress, rather possibly increases the aquifer stress due to the fact that improving irrigation efficiency decreases groundwater abstraction for irrigation, but also reduces return flow or additional recharge from irrigation. Conversely, conjunctive water use of surface water and groundwater facilitates the management of aquifers for more sustainable use and provides pathways for minimizing aquifer stress, developing new opportunities for groundwater development that is environmentally sustainable.

In conclusion, the aquifer stress of many TBAs has been increasing at an alarming rate ($>100\%$) over the past 50 years. In many parts of the world, groundwater resources are under increasing pressure from human water use, such as for irrigation. Future population increase and their food demand will pose a serious threat to the sustainability of these TBAs. The increasing groundwater depletion cast large uncertainties on local farmers, regional food security and countries which import food commodities from TBAs with falling groundwater level. This study gives further evidence to the scale of the issue and its growing trend. It is urging to invest further political efforts to limit the overdraft, however, TBAs traverse international political boundaries over several sovereign countries, which complicates the effective management of these groundwater resources. International laws aiming to preserve TBAs are often limited and multi-states agreements are difficult to achieve due to conflicts of interest among the sovereign countries (Eckstein and Eckstein 2005). However, in recent decades, various regional cooperative networks and agreements have been achieved through dedicated diplomatic structures for shared aquifer management over regions such as the Americas, Europe, and Asia (www.isarm.org/). In order to reduce overexploitation over a TBA and to maximize the beneficial use of the groundwater resources, effective groundwater management through further regional and international efforts is imminent.

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