Past and future contribution of global groundwater depletion to sea-level rise

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[1] Recent studies suggest the increasing contribution of groundwater depletion to global sea-level rise. Groundwater depletion has more than doubled during the last decades, primarily due to increase in water demand, while the increase in water impoundments behind dams has been tapering off since the 1990s. As a result, the contribution of groundwater depletion to sea-level rise is likely to dominate over those of other terrestrial water sources in the coming decades. Yet, no projections into the 21st century are available. Here we present a reconstruction of past groundwater depletion and its contribution to global sea-level variation, as well as 21st century projections based on three combined socio-economic and climate scenarios (SRES) with transient climate forcing from three General Circulation Models (GCMs). We validate and correct estimated groundwater depletion with independent local and regional assessments, and place our results in context of other terrestrial water contributions to sea-level variation. Our results show that the contribution of groundwater depletion to sea-level increased from 0.035 ($\pm$0.009) mm yr^{-1} in 1900 to 0.57 ($\pm$0.09) mm yr^{-1} in 2000, and is projected to increase to 0.82 ($\pm$0.13) mm yr^{-1} by the year 2050. We estimate the net contribution of terrestrial sources to be negative of order -0.15 ($\pm$0.09) mm yr^{-1} over 1970–1990 as a result of dam impoundment. However, we estimate this to become positive of order +0.25 ($\pm$0.09) mm yr^{-1} over 1990–2000 due to increased groundwater depletion and decreased dam building. We project the net terrestrial contribution to increase to +0.87 ($\pm$0.14) mm yr^{-1} by 2050. As a result, the cumulative contribution will become positive by 2015, offsetting dam impoundment (maximum -31 ± 3.1 mm in 2010), and resulting in a total rise of +31 ($\pm$11) mm by 2050. **Citation:** Wada, Y., L. P. H. van Beek, F. C. Sperna Weiland, B. F. Chao, Y.-H. Wu, and M. F. P. Bierkens (2012), Past and future contribution of global groundwater depletion to sea-level rise, *Geophys. Res. Lett.*, *39*, L09402, doi:10.1029/2012GL051230.

1. Introduction

[2] Apart from changes in water stored in glaciers, ice caps and ice sheets, the terrestrial water contribution to sea-level variation include groundwater depletion, water impoundments behind dams, storage loss of endorheic lakes and wetlands, deforestation, and changes in soil moisture, permafrost and snow (i.e., natural water stores) [*Sahagian et al.*, 1994a; *Church et al.*, 2011]. Since its initial assessment [*Sahagian et al.*, 1994a] the contribution of terrestrial water storage change to global sea-level variation has been subject to much debate [*Greuell*, 1994; *Chao*, 1994; *Rodenburg*, 1994; *Gornitz et al.*, 1994; *Sahagian et al.*, 1994b]. Subsequent studies [*Gornitz*, 1995; *Postel*, 1999; *Gornitz*, 2000; *Huntington*, 2008; *Milly et al.*, 2010; *Church et al.*, 2011] differ mostly in their assessment of the contribution of groundwater depletion, owing to differences in methodology and degree of extrapolation [e.g., *Konikow*, 2011]. In the IPCC fourth assessment report [*Intergovernmental Panel on Climate Change*, 2007], the contribution of non-frozen terrestrial waters to sea-level variation is not included due to its perceived uncertainty and the assumption that negative contributions such as dam impoundment compensate for positive contributions (mainly from groundwater depletion). However, recent work on global groundwater depletion [*Wada et al.*, 2010; *Konikow*, 2011] suggests a rapid increase of this positive contribution to sea-level rise during the last decade that warrants a re-appraisal of the contribution of terrestrial waters and in particular groundwater depletion to projected 21st century sea-level change.

2. Estimating Past Groundwater Depletion

[3] We estimate groundwater depletion, defined as the persistent removal of groundwater from aquifer storage owing to abstraction, for the benchmark year 2000 at a 0.5° grid. We use a flux-based method, i.e., calculating the difference between grid-based groundwater recharge (natural recharge and return flow from irrigation as additional recharge) and groundwater abstraction. Compared to volume-based methods that determine groundwater depletion directly from groundwater level observations, groundwater modelling, land-subsidence or GRACE gravity estimation [*Rodell et al.*, 2009; *Tiwari et al.*, 2009; *Famiglietti et al.*, 2011; *Konikow*, 2011; *Scanlon et al.*, 2012], flux-based methods have the disadvantage that they do not take into account increased capture due to decreased groundwater discharge and increased recharge from surface waters. However, volume-based assessments are only available for a limited number of aquifers and regions in the world, such that global estimates can be obtained only through extrapolation under assumptions, such as fixed depletion to abstraction ratios [*Konikow*, 2011], that are difficult to verify.

[4] We retrieved country-based groundwater abstraction rates for the benchmark year 2000 from the IGRAC GGIS data base (http://www.un-igrac.org/). To estimate country-based groundwater abstraction for the years 1900–2000, we then assumed this to increase in proportion to country net

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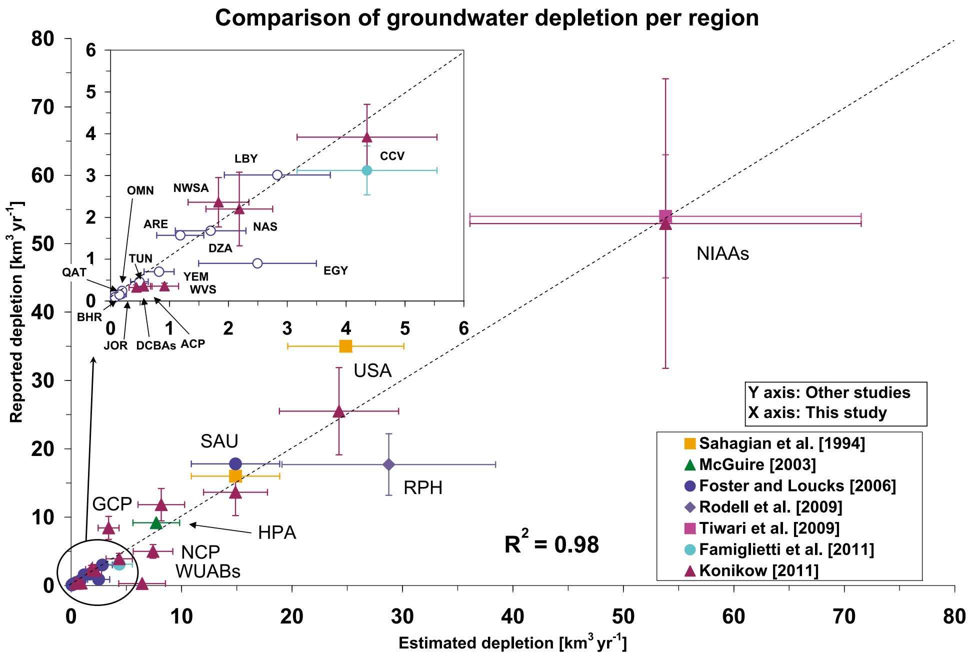

Figure 1. Comparison of corrected groundwater depletion estimates to independent estimates per region [*Sahagian et al.*, 1994a; *McGuire*, 2003; *Foster and Loucks*, 2006; *Konikow*, 2011; *Rodell et al.*, 2009; *Tiwari et al.*, 2009; *Famiglietti et al.*, 2011]. A general multiplicative correction factor was applied to the original estimates for non-arid regions (see also Figure S3–S5 in Text S1). Error bars show standard deviation (s.d.) for each region. Abbreviations used: ACP: Atlantic Coastal Plain; CCV: Central Valley, California; DCBAs: Deep Confined Bedrock Aquifers; GCP: Gulf Coastal Plain; HPA: High Plains (Ogallala) Aquifer; NAS: Nubian Aquifer System; NIAAs: Northern India and Adjacent Areas; NCP: North China Plain; NWSAS: North Western Sahara Aquifer System; RPH: Rajasthan, Punjab, Haryana; WUABs: Western USA Alluvial Basins; WVSs: Western Volcanic Systems. Countries are identified by their ISO country codes. The dashed line represents the 1:1 slope.

total water demand (see Figure S1 in Text S1 in the auxiliary material for validation of this assumption).[1] Next, we calculated grid-based (0.5°) estimates of groundwater abstraction by downscaling country-based groundwater abstraction rates, using the difference between surface freshwater availability and net total water demand as proxy. Comparison of the resulting abstraction maps with reported county abstractions for the U.S. shows that this downscaling method performs well (see Figure S2 in Text S1). We refer to *Wada et al.* [2011a, 2011b, 2012] and the auxiliary material for details on the calculation of global surface water availability and net total water demand.

[5] The difference between grid-based groundwater recharge (natural recharge and return flow from irrigation as additional recharge) and abstraction yielded an estimate of groundwater depletion. An uncertainty analysis of simulated groundwater recharge, estimated groundwater abstraction and resulting groundwater depletion were performed according to *Wada et al.* [2010] (see also auxiliary material). To validate our estimates for groundwater depletion, we compared these for the year 2000 with independent, mostly volume-based, estimates from different regions between 1990 and 2010 [*Sahagian et al.*, 1994a; *McGuire*, 2003; *Foster and Loucks*, 2006; *Konikow*, 2011; *Rodell et al.*, 2009; *Tiwari et al.*, 2009; *Famiglietti et al.*, 2011]. Although the timeframe for the comparison is limited and does not exactly correspond to one another, it generally shows good agreement (see Figure S4 in Text S1). Our method, however, slightly overestimates reported depletion for the non-arid areas of the world, which we attribute to increased capture due to enhanced recharge from surface water. To remediate this overestimation, we applied a general multiplicative correction factor for these regions (see auxiliary material). After tuning, Figure 1 compares our corrected estimates with those from other studies, now showing excellent agreement. It should be noted that a recent study by *Shamsudduha et al.* [2012] with ground-based observations showed that groundwater depletion estimates for the humid tropics (e.g., Bangladesh) derived from GRACE satellite data might be subject to large uncertainties. Yet, most of the depletion occurs in (semi-) arid regions (e.g., North West India and North East Pakistan). Based on the corrected depletion rates (see Figure S5 and S6 in Text S1), we estimate a global depletion rate of 204 (±30) $km^3\ yr^{-1}$ for the year 2000, equivalent to a sea-level rise of 0.57 (±0.09) $mm\ yr^{-1}$. We applied the same correction to past estimates and future projections.

3. Projecting 21st Century Groundwater Depletion

[6] We projected future groundwater depletion into the 21st century using socio-economic projections from three IPCC SRES scenarios (A1b, A2, B1) and bias-corrected meteorological forcing from General Circulation Models (GCMs). For each scenario, we used country and regional data on projected socio-economic development and land use

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL051230.

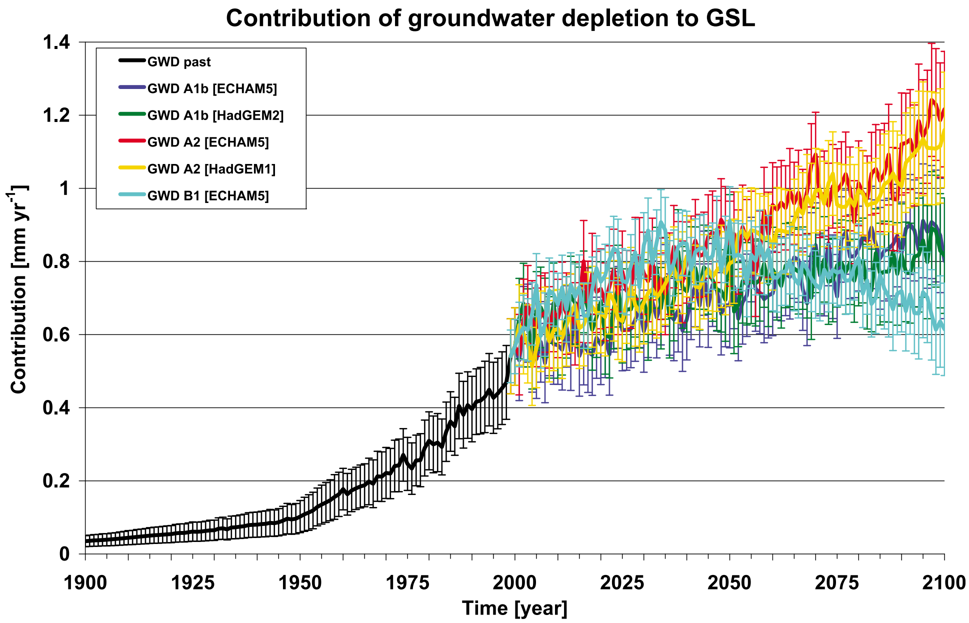

Figure 2. Time series of the estimated and projected contribution of groundwater depletion (GWD) to global sea-level (GSL) over the period 1900–2100. Projections are based on three scenarios (A1B, A2, B1) with three different GCMs (ECHAM5, HadGEM1, HadGEM2) (five projections in total). Error bars show standard deviation (s.d.) for each scenario projection from each GCM. GCM meteorological outputs were bias-corrected on a grid-by-grid basis (0.5°).

retrieved from the IPCC SRES scenarios data portal (http://www.ipcc-data.org/) and corresponding population data from *Gaffin et al.* [2004]. Associated climate forcing was obtained for the period 1951–2100 from transient runs at daily time step of the following GCMs: ECHAM5 (A1b, A2, B1), HadGEM1 (A2) and HadGEM 2 (A1b). We selected these GCMs based on the availability of transient daily climate data (*i.e.*, precipitation and temperature). GCM output was bias-corrected on a grid-by-grid basis for mean monthly temperature, precipitation amount and number of wet days by scaling the long-term monthly means of the GCM daily fields to those of the CRU TS 2.1 data set [*Mitchell and Jones*, 2005] for the overlapping reference climate 1961–1990 (see auxiliary material). The resulting bias-corrected transient climate fields were used to force the global hydrological model PCR-GLOBWB [*van Beek et al.*, 2011]

Table 1. Global Sea-Level Budget With the Estimates of *Konikow* [2011] Compared With Those of This Study for Groundwater Depletion (Our Estimates in Bold) for Two Different Time Intervals (1972–2008 and 1993–2008) in mm yr^{-1}[a]

Component (mm yr^{-1})	Reference	1972–2008	1993–2008
	Observed		
Total sea-level rise (t.g.)		1.83 ± 0.18	2.61 ± 0.55
Total sea-level rise (t.g. + sat)		2.10 ± 0.16	3.22 ± 0.41
	Estimated		
Component (mm yr^{-1})	Reference	1972–2008	1993–2008
Thermal expansion (full depth)	*Church et al.* [2011]	0.80 ± 0.15	0.88 ± 0.33
Land ice (glaciers, ice caps, ice sheets)	*Church et al.* [2011]	1.09 ± 0.26	1.73 ± 0.27
Groundwater depletion	*Konikow* [2011]	0.26 ± 0.07	0.35 ± 0.07
	This study	**0.42 ± 0.08**	**0.54 ± 0.09**
Terrestrial storage change	*Church et al.* [2011]	−0.11 ± 0.19	−0.08 ± 0.19
	This study	**0.05 ± 0.20**	**0.10 ± 0.20**
Total sea-level rise	*Church et al.* [2011]	1.78 ± 0.36	2.54 ± 0.46
	This study	**1.94 ± 0.36**	**2.71 ± 0.47**
	Observed – Estimated		
Residual (t.g.)	*Church et al.* [2011]	0.05 ± 0.40	0.08 ± 0.72
	This study	**−0.11 ± 0.40**	**−0.10 ± 0.72**
Residual (t.g. + sat)	*Church et al.* [2011]	0.32 ± 0.39	0.69 ± 0.62
	This study	**0.16 ± 0.39**	**0.51 ± 0.62**

[a]Estimated sea-level rates were compared with observed rates from the reconstructed tide-gauge data (t.g.) and from joining the altimeter data to the reconstructed data in 1993 (t.g. + sat). The observed and estimated sea-level budgets were taken from *Church et al.* [2011]. Dam retention (i.e., water impoundments behind dams) and natural terrestrial storage remain the same as those from *Church et al.* [2011] for the comparison.

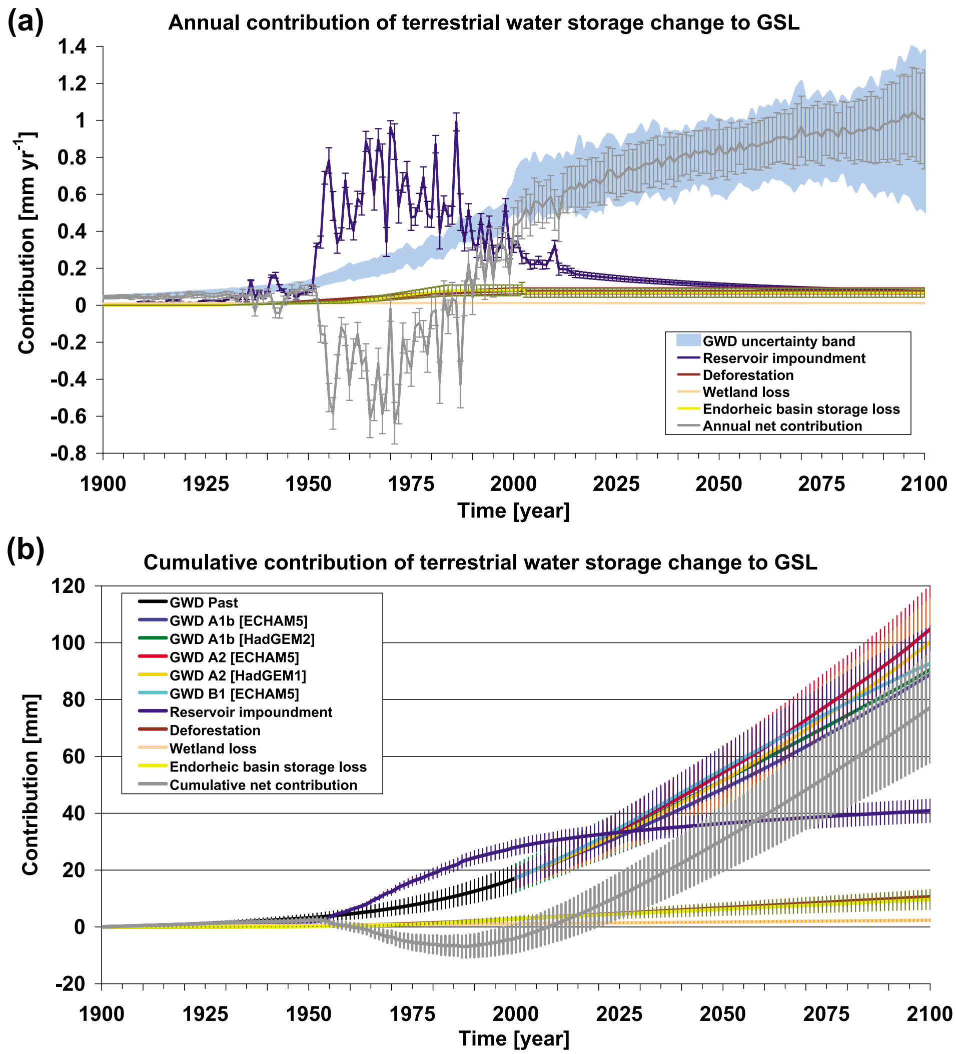

Figure 3. Time series of the estimated and projected (a) annual contribution of terrestrial water storage change to global sea-level over the period 1900–2100 (rates in mm yr^{-1}) and (b) cumulative contribution of terrestrial water storage change to global sea-level over the period 1900–2100 (in mm). To estimate the mean and standard deviation over the ensemble of the five groundwater depletion projections, we used the mean and standard deviation from each projection as parameters in an assumed Gaussian distribution, and drew 2000 (Monte Carlo) realizations for each projection. We subsequently calculated the mean and standard deviation from the resulting 10000 realizations (five projections in total). GWD (groundwater depletion) total uncertainty band (light blue) was taken from the maximum and minimum uncertainty range of past estimates (1900–2000) and five projections (2001–2100) for each year.

for 2001–2100. As for the period 1900–2000, we assumed country-based groundwater abstraction to change in proportion to corresponding country net total water demand over the projected period.

4. Results: Past and Future Global Groundwater Depletion

[7] During the 20th century, the contribution of groundwater depletion to global sea level increased from 0.035 ($\pm$0.009) mm yr^{-1} in 1900 to 0.57 ($\pm$0.09) mm yr^{-1} in 2000, and is projected to increase to 0.82 ($\pm$0.13) mm yr^{-1} by year 2050 (see Figure 2). The increase from 1900 to 2000 is primarily driven by increased water demand, while the projected increase from 2001 to 2050 is mostly climate-driven, arising from decreased surface water availability and groundwater recharge in combination with larger evaporative demand over irrigated areas following increased temperatures. Beyond the year 2050, average depletion increases even further (see also Animation S1 in the auxiliary material), but differences between scenarios become very large. Also, projections of groundwater depletion too far into the 21st century become progressively more hypothetical as groundwater may either become unattainable, e.g., in deep alluvial aquifers, or fully depleted, e.g., in hard rock aquifers of limited porosity.

[8] *Church et al.* [2011] recently reviewed sea-level change from all sources (thermal expansion, Antarctic and Greenland ice sheets, ice caps and glaciers, and terrestrial water storage) and compared the total reconstructed signal to estimates of sea-level rise for the periods 1972–2008 and 1993–2008 from tide gauges (t.g.) and a combination of tide gauges and satellite observations (t.g. + sat) (see Table 1). We substituted our estimates for groundwater depletion into

this global sea-level budget instead of the estimates taken from *Konikow* [2011]. The results generally show similar residuals, although the residuals are slightly smaller for t.g. + sat when using our estimates. It should be noted that the recent study by *Jacob et al.* [2012] using GRACE satellite data estimates a smaller contribution of glaciers and ice caps to sea-level rise (0.41 $\pm$ 0.08 mm yr^{-1} over the period 2003–2010) compared to the estimate used in *Church et al.* [2011] (0.99 $\pm$ 0.04 mm yr^{-1} over the period 1993–2008). Although the timeframes differ, using the estimate by *Jacob et al.* [2012] results in a larger residual between observed and estimated total sea-level rise.

5. Results: Groundwater Depletion Among Other Terrestrial Sources

[9] We also placed our reconstructed and projected contributions to global sea level rise in the context of other terrestrial sources. We included and extrapolated impoundment by dam building, deforestation, wetland loss and storage change in endorheic basins and lakes. We did not include natural terrestrial storage change (e.g., soil moisture, permafrost and snow) because this mostly varies with decadal climate variation. We obtained data on dam impoundment, including additional storage in surrounding groundwater (through seepage) from *Chao et al.* [2008]. As this dataset only covers the period 1900–2007, we updated the effects of the Three Gorges dam and 250 other recent dams up to the year 2011. To extrapolate this dataset towards 2100, we plotted the cumulative reservoir volume stored behind dams and fitted a smooth function. Rates for 2100 were subsequently estimated by taking derivatives. We estimated deforestation from three different sources [*Sahagian*, 2000; *Food and Agriculture Organization of the United Nations*, 2001; *Achard et al.*, 2002] and assumed it to continue at a constant rate. Wetland loss for the U.S. [*Sahagian et al.*, 1994a; *Sahagian*, 2000] was extrapolated to that of the world using three global wetland datasets [*Matthews*, 2000; *Lehner and Döll*, 2004; *Bicheron et al.*, 2010], assuming wetland loss to be proportional to wetland area. Storage loss from endorheic basins (mostly the Aral Sea) was estimated from earlier work [*Sahagian et al.*, 1994a] but updated with a recent storage increase of the northern basin of the Aral Sea [*Pala*, 2006, 2011]. For detailed descriptions of the uncertainty assessment of these trends, we refer to the auxiliary material.

[10] We estimate the net contribution of terrestrial sources to be slightly positive during the early decades of the 20th century (see Figure 3a). After that, the contribution becomes consistently negative and an order of -0.15 ($\pm$0.09) mm yr^{-1} during 1970–1990 as a result of water impoundment behind dams. As dam building has been tapering off since the 1990s, while groundwater depletion steadily increasing, the net contribution has become positive of order +0.25 ($\pm$0.09) mm yr^{-1} over the period 1990–2000 and is projected to increase to +0.87 ($\pm$0.14) mm yr^{-1} by the year 2050. Considering the cumulative contribution (see Figure 3b), the negative effect of dam building reaches a maximum of -31 ($\pm$3.1) mm in 2010 and, taking the mean of the scenarios, is projected to be compensated by positive contributions by around the year 2015 and to reach a value of +31 ($\pm$11) mm by the year 2050 (see Table S2 in Text S1).

[11] We note that our estimates and projections are inherently uncertain, as a result of the data and methods used and the imposed scenarios of climate and socio-economic development as depicted by the estimated uncertainty bands (Figure 3a). A series of assumptions were employed to overcome the lack of input data (see auxiliary material). Notwithstanding, our results compare well with independent estimates for the present groundwater depletion rates (Figure 1) and show that groundwater depletion is likely to be the major component of terrestrial contribution to sea-level change in the coming decades.

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