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1) The definition of hydrologically-active regional aquifers

A global inventory of groundwater resources[1] mapped the world in three categories: major groundwater basins, areas with complex hydrogeologic structures, and areas with local and shallow aquifers. We considered regional aquifers to be the major groundwater basins, assuming the other two categories have locally rather than regionally important groundwater resources. Further, we focused on regional aquifers with a mapped recharge rate > 2mm·year^{-1}. Average recharge rates from PCR-GLOBWB for these same aquifers were also generally > 2mm·year^{-1}; when the estimated recharge was lower, a minimum recharge of 2mm·year^{-1} was imposed. By focusing on major groundwater basins with a recharge rate > 2mm·year^{-1} we are conservatively evaluating hydrologically-active, regionally to nationally important groundwater resources[1]. This calculation is conservative because lower recharge rates lead to larger groundwater footprints.

2) Mathematical relationship between the groundwater footprint and ecological footprint

The ecological footprint (*EF*) is formally defined as

$$EF = aa \cdot N \qquad \text{(Equation 1)}$$

where *aa* (units km^2/capita) is the land area appropriated per capita and *N* is the population size[2]. The land area appropriated per capita is calculated using

$$aa = \frac{c}{p} \qquad \text{(Equation 2)}$$

where *c* is the average annual consumption per capita ($m^3 capita^{-1} y^{-1}$) and *p* is the average annual yield ($m^3 km^{-2} y^{-1}$). For groundwater we consider the average annual yield (*p*) is the long-term, natural recharge plus the artificial recharge due to irrigation (*i.e.* $R_{natural} + R_{irrigation}$) minus the flux out of system (*i.e.* discharge or *D*) allocated for environmental flows (*E*) as shown in Figure S1. Other expressions of *P* are discussed below in Section 4. We calculate the groundwater footprint based on area-averages rather than per capita population averages due to data availability. However, the groundwater footprint is a mathematically equivalent area-based method to the population-based ecological footprint.

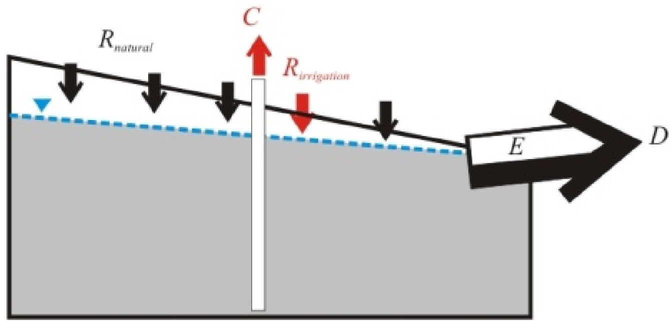

Figure S1. A schematic cross-section of an aquifer with inputs and outputs. At steady-state, natural recharge ($R_{natural}$) to a groundwater system equals the discharge (D) or baseflow to surface water systems. Abstraction of groundwater (C) can increase recharge or decrease discharge[3,4]. Irrigation with groundwater can result in artificial recharge ($R_{irrigation}$)[5]. The minimum environmental low flow (E) is a component of D. The unconfined aquifer is the grey area below the water table (blue dashed line).

3) Mathematical relationship between groundwater footprint and previous water stress indicators

The area-normalized groundwater footprint is an indicator of groundwater stress worldwide that is similar to previous stress indicators (Table S1).

Table S1. Summary of stress indicators

	Previous work (surface water focused)[6-9]	This study (groundwater focused)
Resource stress indicators	$WSI = \frac{withdrawls}{MAR}$	$\frac{GF(E=0)}{A} = \frac{C}{R}$ see Table S2
Environmental stress indicators	$EWSI = \frac{withdrawls}{MAR - E}$	$\frac{GF}{A} = \frac{C}{R-E}$ see Table 1

Where *WSI* is the water stress indicator, *MAR* is the mean annual runoff, *EWSI* is the environmental water stress indicator and other variables are defined in the text.

4) Other forms of the groundwater footprint equation for local calculations

We derived various expressions for the average annual yield (p) which can be applied depending of the type of data available at the scale of analysis. All equations assume an unconfined aquifer with constant saturated thickness, porosity and areal recharge flux. For groundwater systems where the full geometry (volume and area) are known, a useful expression is

$$p = \frac{V\varphi}{\tau A} - E \qquad \text{(Equation 3)}$$

where V (m^3), φ (unitless), τ (y) and A (m^2) are the volume, porosity, mean residence time and area, respectively, of the aquifer. The mean residence time of an aquifer is defined as the average time for groundwater to flow from recharge to discharge areas[10,11]. It is highly heterogeneous from years to millennia and even millions of years. For groundwater systems where only the aquifer thickness is well constrained,

$$p = \frac{z\varphi}{\tau} - E \qquad \text{(Equation 4)}$$

where z (m) is the saturated thickness. For aquifers with assumed exponential flow paths the average annual yield can be simply expressed as

$$p = R - E \qquad \text{(Equation 5)}$$

where R (m/y) is the areal recharge flux, respectively, of the aquifer since

$$\tau = \frac{\varphi z}{R} \qquad \text{(Equation 6)}$$

as shown by *McMahon et al*[12]. Equation 5 is used to calculate global groundwater footprints herein.

5) Detailed Methods

a. Downscaling country-based groundwater abstraction to the grid-scale

Since the exact locations where groundwater is abstracted by wells are not known for most of the countries, we downscale country-based groundwater abstractions from the IGRAC GGIS data base [*International Groundwater Resources Assessment Centre*; http://www.igrac.net/], indexed for the year 2000, by taking the available surface freshwater into account[5]. We assume that grid cells with deficits (*i.e.*, water demand in excess of surface water availability) are the main locations where groundwater is abstracted to satisfy the demand. For each month, m, in the year 2000 and for each grid cell, i, we calculate deficits, $Defs_{m,i}$, between the surface water availability, $A_{m,i}$, simulated by PCR-GLOBWB (after correcting for upstream water consumption) and the estimated net total water demand, $D_{T_{Net},m,i}$. Because we are interested in groundwater as an alternative source we limit this analysis to regions where the aquifers are present (major groundwater regions of the world according to the IGRAC GGIS; http://www.un-igrac.org/publications/119). We sum monthly values to obtain the annual deficits, $Defs_{a,i}$, for the year 2000.

$$Defs_{a,i} = \sum_{m=1}^{12} Defs_{m,i} = \sum_{m=1}^{12}\left(D_{T_{Net},m,i} - A_{m,i}\right) \qquad \text{(Equation 7)}$$

The annual deficits, $Defs_{a,i}$, are met by the amount of available country groundwater abstraction until surface water availability and groundwater abstraction satisfy the total water demand. Total deficits per country, $Defs_a$, are given by:

$$Defs_a = \sum_{i=1}^{n} Defs_{a,i} \, , \qquad \text{(Equation 8)}$$

where n is the number of grid cells with deficits per country. If the total deficits are larger than the available groundwater abstraction in a country, $Defs_a > Groundw_a$, (*e.g.*, Egypt, Sudan, Mali, Niger, Sudan, Turkmenistan and Uzbekistan), we distribute the country abstraction according to the intensities rather than the volume of the deficits. In case the available abstraction is larger than the total deficits in a country, the remaining country-based abstraction ($Groundw_a$ - $Defs_a$) is further allocated relative to the intensity of total water demand over its country total (again limited to cells in major groundwater regions):

$$Groundw_{a,i} = Defs_a + \left(Groundw_a - Defs_a\right) \cdot \frac{D_{T_{Net},a,i}}{\sum_{i=1}^{n} D_{T_{Net},a,i}} \qquad \text{(Equation 9)}$$

We validated the downscaled groundwater abstraction against reported values for a number of large groundwater consumers (the conterminous USA, Mexico, India and China). Sources of subnational groundwater abstraction data are outlined below in Section 6. In all cases these are comparisons on the basis of administrative units, generally at the level of states or provinces except for the USA for which also county-level information is available (used earlier for validation in *Wada et al.* [5]). Here, the match between the reported and estimated values (downscaled to cell-values and subsequently aggregated) is presented graphically in Figure S4 while statistics on performance are summarized in Table S3. Although the estimated values are derived from a single, country-based value, the spatial distribution agrees well with the reported values at the sub-national level as we explicitly account for the spatio-temporal variations in the deficit between total demand and surface water availability and include information on aquifer extent. Still, the downscaled values are generally lower than the reported ones, with the exception of Mexico. For Mexico, relatively large overestimations are found for three states (Sinaloa, Sonora and Tamaulipas) that have large irrigation water demands which are primarily drawn from surface water, rather than groundwater. In contrast, but less extreme, groundwater abstraction is underestimated in Yucatan where allegedly all reported water use issues from groundwater. A similar tendency can be observed also for the adjacent states of the Yucatan peninsula. Notwithstanding, performance is generally good, even at the fine level of the counties of the conterminous USA, and indicates that the downscaling method is adequate to downscale the country-based groundwater abstraction of the IGRAC dataset to the value of individual cells and that the results are of sufficient quality to assess the effects of groundwater exploitation on regional resources at the global scale.

b. Recharge due to irrigation

To account for the artificial groundwater recharge due to irrigation that possibly mitigates groundwater depletion in areas of large irrigation water withdrawals[13], we used the data from *Wada et al.*[5] The return flow to groundwater during irrigation application or artificial recharge is estimated to be 420 km^3•$year^{-1}$ out of a total gross irrigation water demand of 2510 km^3•$year^{-1}$. This artificial groundwater recharge was computed from the principle 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 soil water capacity can percolate to the groundwater system. The additional recharge rate thus equals the unsaturated hydraulic conductivity of the top 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.*[14].

c. Environmental flows

The streamflow contribution from the renewable groundwater (i.e., baseflow) is essential for ecosystem services, sustaining freshwater habitats and associated ecosystems, in particular during low-flow conditions when the contribution from other sources is small. To include this essential aspect of groundwater resources in our analysis in addition to the mere supply of human demand, we identified the environmental flow conditions as the monthly streamflow that is exceeded in 90%, Q_{90}, of the simulated cases over the period 1958-2000. This streamflow results from the specific runoff over the land surface proper, including baseflow, and that over the freshwater surface (streams, lakes and reservoirs), which consists of direct gains from precipitation and losses from evaporation. Under the assumption that all sources contribute equally to the streamflow, mean discharge at the outlet can be approximated by accumulating all positive contributions along the drainage network with any negative losses over freshwater surfaces acting as sink. Thus, specific runoff from the land surface may have to compensate for losses farther downstream and heighten the fraction of renewable groundwater recharge that has to be reserved to safeguard environmental flow at the basin outlet:

$$f_{Q_{90}} = \frac{Q_{90}}{\overline{Q}} \times \frac{\sum \overline{q}_{land}}{\overline{Q}} \qquad \text{(Equation 10)}$$

where $f_{Q_{90}}$ is the fraction of groundwater recharge to be reserved to meet the environmental streamflow Q_{90}, $\overline{Q}$ is the mean discharge at the outlet and $\sum \overline{q}_{land}$ is the accumulated mean specific runoff from the land surface, all flows being represented as volumes over the basin and per year.

Here, the first ratio relates the environmental flow conditions to the mean runoff, including baseflow from recharge, while the second ratio compensates for downstream losses. Although $f_{Q_{90}}$ provides a uniform fraction over the basin it indirectly accounts for local variations in recharge and changes the absolute amount of renewable groundwater for abstraction on a cell-by-cell basis. The computed $f_{Q_{90}}$ fractions are generally substantially larger than 10% of the recharge (Figure S2).

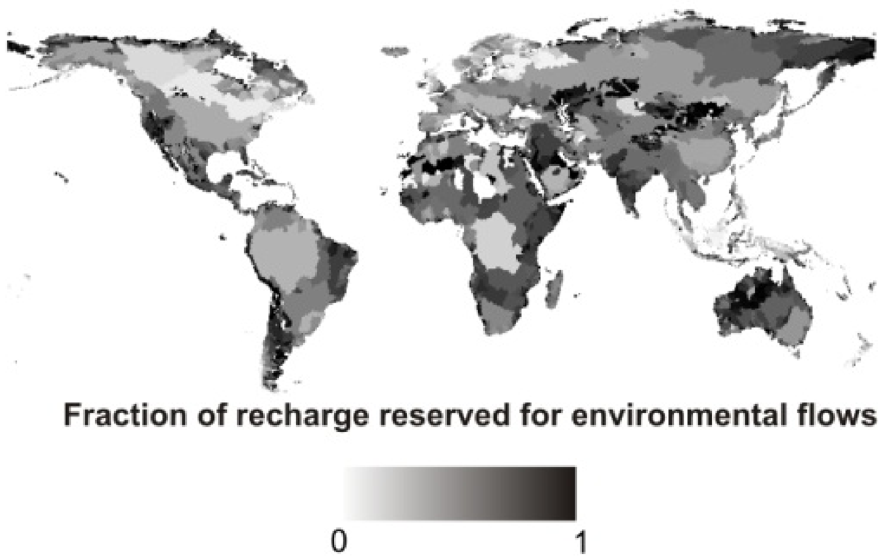

Figure S2. Fraction of the recharge reserved for environmental flow ($f_{Q_{90}}$) per river basin.

d. The global groundwater footprint

The global groundwater footprint is calculated as the sum of the groundwater footprints for individual hydraulically-aquifer, regional aquifers.

e. Population impacted by groundwater stress

The population impacted by groundwater stress (Figure 2b) was calculated as people living on hydraulically-active, regional aquifers with a ratio of groundwater footprint to aquifer area >1. About 60% of the global population impacted by groundwater stress live in India and China. Population densities were derived from the gridded population of the world for year 2000 at 0.25° resolution[15]. To account for the uncertainty, we calculated the mean and standard deviation of the global populations over which a ratio of groundwater footprint to aquifer area > 1, as resulting from 10 000 Monte Carlo realizations for the groundwater footprint (see **Methods Summary**).

f. New calories and groundwater stress

Foley et al[16] calculated the global distribution of potential new calories that could be derived by bringing the world's agricultural yields to within 95% of their potential for 16 major crops. We directly overlaid Figure 3 from Foley et al[16], with our classification of regional aquifers as more stressed or less stressed (Figure 1). We kept the same shading scale as Figure 3 of Foley et al[16] so that no information was lost or re-interpreted.

6) Sources of Data

All data used in this manuscript is freely available either by contacting the authors or from data download archives. The sources of data are as follows:

- Recharge, groundwater consumption and environmental flow data is available in an enclosed zip file. The enclosed SI Guide.txt outlines the projection information.
- Groundwater aquifer polygons are available by contacting BGR-WHYMAP: http://www.whymap.org/whymap/EN/Home/whymap_node.html
- Gridded population density (persons per km2) Year 2000 can be downloaded from http://sedac.ciesin.columbia.edu/gpw.
- Potential diet gap was calculated[16] in kilocalories that are potentially available if directly consumed but are lost post-production by going to animal feed and other uses as reported in FAO trade data. Kilocalories were calculated by converting production in tonnage [17] (data available http://www.geog.mcgill.ca/landuse/pub/Data/175crops2000/) to kilocalories following Tilman et. al.[18].

Sources of data for analysis of downscaled groundwater abstraction:

- China: Ministry of Environmental Protection. 2007. Freshwater Environment. http://english.mep.gov.cn/standards_reports/EnvironmentalStatistics/yearbook2006/200712/t20071218_115211.htm
- India: Central Ground Water Board. 2004. Dynamic Ground Water Resources of India 2004. http://www.cgwb.gov.in/documents/DGWR2004.pdf
- United States: USGS. 2012. Water use in the United States. http://water.usgs.gov/watuse/
- Mexico: CONAGUA. 2008. Statistics on water in Mexico 2008. http://www.conagua.gob.mx/english07/publications/Statistics_Water_Mexico_2008.pdf

7) Aquifers with large groundwater footprints that are not well documented

A number of aquifers with large groundwater footprints (e.g. the Persian, Arabian and Western Mexico aquifers) have not been well documented in the main hydrological literature. However, evidence of groundwater depletion of these aquifers been reported elsewhere. A recent study by *Karimi et al*[19] indicates that in certain areas of Iran the groundwater table has dropped by rate of up to 1 meter per year for the last 10 years, primarily in regions with agricultural areas where farmers heavily rely on groundwater for irrigation. They also estimate that the groundwater table has declined with an average of 0.4 meter per year across the country for the same time period. Similarly, *Soltani and Saboohi* [20], *Khodapanah et al*[21] and *Jaghdani and Brümmer* [22] indicate that excessive groundwater overdraft for irrigation has caused substantial groundwater depletion over many parts of Iran. In Mexico where 80% of water is used for agriculture, excessive groundwater overdraft is also prevalent according to Guevara-Sanginés[23]. They report that more than half of the 188 most important aquifers have been overexploited, and the overexploitation is most severe over northern, western and central Mexico, where abstraction rates are considerably larger than the rate of recharge. Over Saudi Arabia where, compared to other regions, groundwater recharge is substantially lower due to its arid climate, large irrigation water use is sustained by nonrenewable groundwater abstraction. *Foster and Loucks*[24] states that cumulative groundwater depletion from 1980 to 2000 exceeds 250 km^3 (average >12 km^3 yr^{-1}).

8) Additional Results

Table S2. Groundwater footprint (*GF*) and aquifer area (*AA*) of the aquifer with the largest groundwater footprints without considering environmental flows (*E*=0). The values of for *GF* and *GF/AA* are the mean and standard deviation of 10,000 Monte Carlo realizations based on independent estimates of recharge and abstraction[5]. Note that only 15 aquifers with largest groundwater footprint are tabulated but the 768 'other aquifers' are included in 'all aquifers'. The *GF/AA* is calculated before rounding the *GF* to one decimal place.

Aquifer	Country	*GF* (*E*=0) (10^6 km^2)	*AA* (10^6 km^2)	*GF*(*E*=0)/*AA*
Upper Ganges	India, Pakistan	17.3 ± 5.7	0.48	35.9 ± 11.9
North Arabian	Saudi Arabia	15.2 ± 4.5	0.36	42.5 ± 12.5
South Arabian	Saudi Arabia	8.1 ± 3.2	0.25	32.8 ± 12.9
Persian	Iran	6.9 ± 2.7	0.42	15.9 ± 6.3
South Caspian Sea	Iran	5.3 ± 1.8	0.06	90.8 ± 30.8
Western Mexico	Mexico	4.7 ± 1.4	0.21	22.5 ± 6.8
High Plains	USA	3.3 ± 1.0	0.50	6.5 ± 2.0
Lower Indus	India, Pakistan	2.2 ± 0.7	0.23	9.6 ± 3.2
Nile delta	Egypt	2.2 ± 0.7	0.10	22.5 ± 6.9
Central Mexico	Mexico	1.1 ± 0.3	0.20	5.3 ± 1.3
North China Plain	China	1.0 ± 0.4	0.23	4.4 ± 1.5
Danube Basin	Hungary, Austria, Romania	1.0 ± 0.4	0.32	3.2 ± 1.2
Northern China	China	0.7 ± 0.2	0.31	2.2 ± 0.6
North Africa	Algeria, Tunisia, Libya	0.5 ± 0.2	0.36	1.3 ± 0.4
Central Valley	USA	0.4 ± 0.1	0.07	5.9 ± 1.6
Other aquifers		**6.6 ± 2.0**	**34.17**	**0.2 ± 0.1**
All aquifers		**76.5 ± 15.7**	**38.25**	**2.0 ± 0.4**

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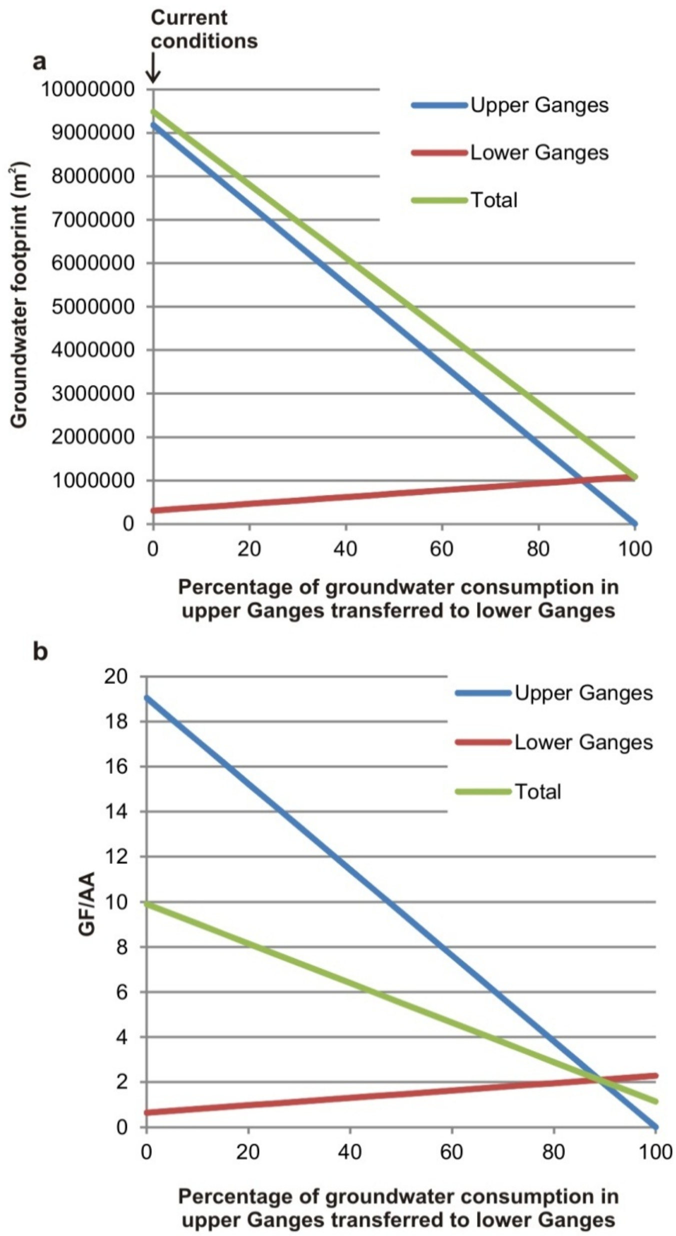

Figure S3. Scenario tests of transferring groundwater consumption from Upper Ganges to Lower Ganges in northern India. The upper Ganges aquifer has a approximately ten times lower recharge rate than the Lower Ganges aquifer so transferring groundwater consumption results a significant decrease in the groundwater footprint of the Upper Ganges and a moderate increase in the groundwater footprint of the Lower Ganges. The net impact is significant lower total groundwater footprint.

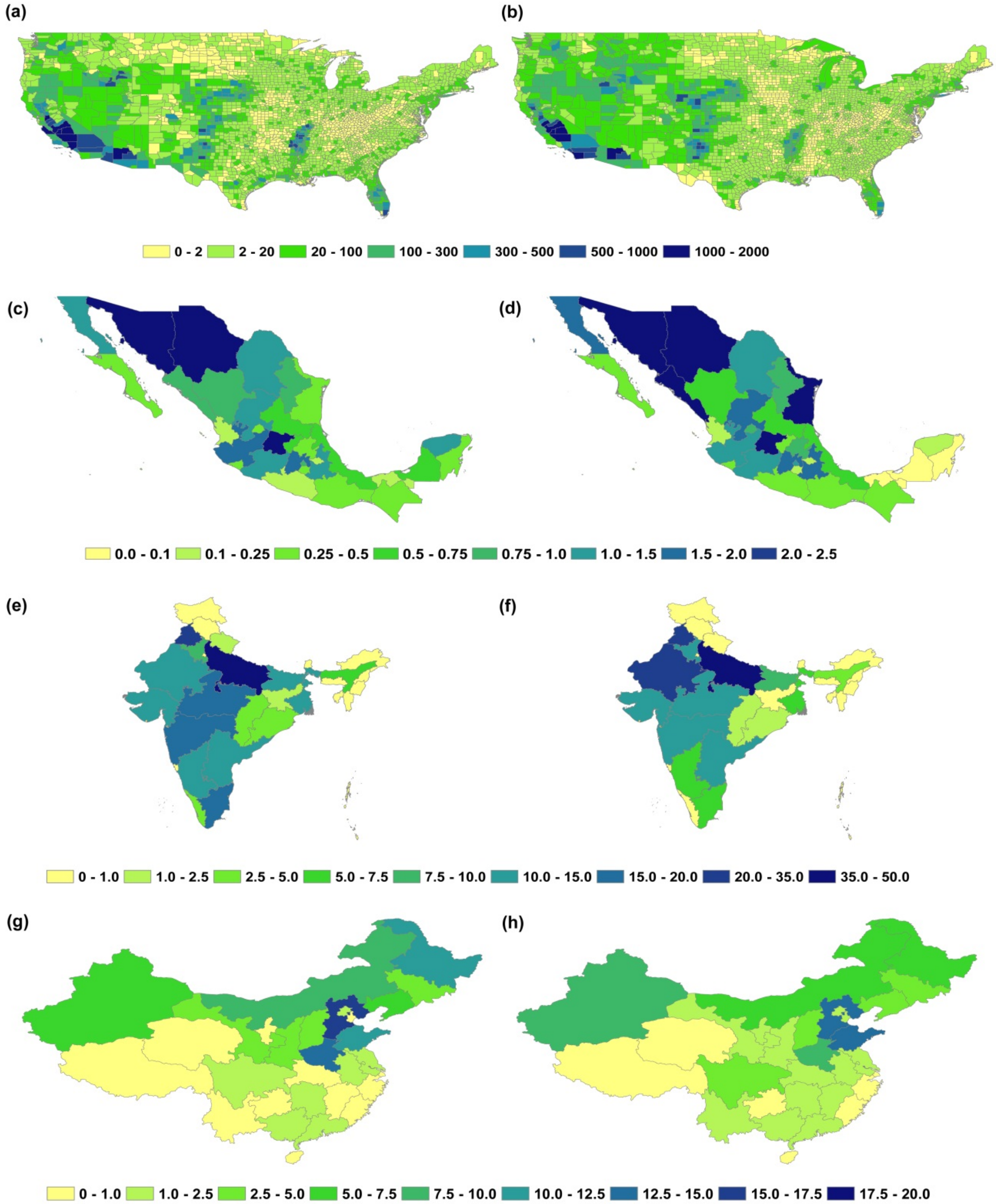

Figure S4: Comparison of reported and estimated groundwater abstraction for the year 2000 for selected major groundwater consumers. Data are derived for conterminous USA per county, Mexico per state, India per state, China per province. (a) USA reported, (b) USA modeled; (c) Mexico reported, (d) Mexico modeled; (e) India reported, (f) India modeled; (g) China reported, (h) China modeled. Estimated values are derived from the spatially downscaled country-based totals. All abstractions are in $km^3 \cdot year^{-1}$ with the exception of the USA, for which the county values are given in 10^6 $m^3 \cdot year^{-1}$.

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Country	Level	GW abstraction	Unit	Total	Mean	Standard deviation	RMSE	Regression Regression coefficient [-]	Standard error [-]	R^2 [-]	Number of observations
USA	County	Reported	10^6 $m^3 \cdot year^{-1}$	95695.8	36.2	120.8	56.497	0.939	0.009	0.803	2644
		Estimated		90811.6	34.3	115.3					
	State	Reported	$km^3 \cdot year^{-1}$	115.4	2.4	4.0	34.059	0.954	0.035	0.939	48
		Estimated		109.2	2.3	4.1					
Mexico	State	Reported	$km^3 \cdot year^{-1}$	28.9	0.9	0.8	0.801	0.643	0.062	0.778	32
		Estimated		36.2	1.1	1.2					
India	State and territory	Reported	$km^3 \cdot year^{-1}$	230.6	6.6	10.4	3.971	1.013	0.060	0.895	35
		Estimated		196.6	5.6	10.1					
China	Province	Reported	$km^3 \cdot year^{-1}$	103.9	3.5	4.2	1.564	1.081	0.058	0.922	30
		Estimated		96.4	3.2	3.6					

Table S3: Summary statistics for the comparison of reported and estimated (downscaled) groundwater abstraction of Figure S4. Reported abstraction is regressed on the estimated values with the regression line forced through the origin. Regression coefficients below unity are indicative of overestimation, over unity of underestimation. 2644 out of 3119 possible counties within the conterminous USA were selected for which the absolute deviation in area was less than 5%, mostly excluding the smaller states and those along the coast or borders.

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