

Water balance of global aquifers revealed by groundwater footprint

Tom Gleeson¹, Yoshihide Wada², Marc F. P. Bierkens^{2,3} & Ludovicus P. H. van Beek²

Groundwater is a life-sustaining resource that supplies water to billions of people, plays a central part in irrigated agriculture and influences the health of many ecosystems^{1,2}. Most assessments of global water resources have focused on surface water^{3–6}, but unsustainable depletion of groundwater has recently been documented on both regional^{7,8} and global scales^{9–11}. It remains unclear how the rate of global groundwater depletion compares to the rate of natural renewal and the supply needed to support ecosystems. Here we define the groundwater footprint (the area required to sustain groundwater use and groundwater-dependent ecosystem services) and show that humans are overexploiting groundwater in many large aquifers that are critical to agriculture, especially in Asia and North America. We estimate that the size of the global groundwater footprint is currently about 3.5 times the actual area of aquifers and that about 1.7 billion people live in areas where groundwater resources and/or groundwater-dependent ecosystems are under threat. That said, 80 per cent of aquifers have a groundwater footprint that is less than their area, meaning that the net global value is driven by a few heavily overexploited aquifers. The groundwater footprint is the first tool suitable for consistently evaluating the use, renewal and ecosystem requirements of groundwater at an aquifer scale. It can be combined with the water footprint and virtual water calculations^{12–14}, and be used to assess the potential for increasing agricultural yields with renewable groundwater¹⁵. The method could be modified to evaluate other resources with renewal rates that are slow and spatially heterogeneous, such as fisheries, forestry or soil.

The ecological footprint and the water footprint are powerful, popular and complementary tools for planning, education and public awareness, but their methodologies are fundamentally different¹³. The ecological footprint is the land area (in km²) required to sustain a population¹⁶, whereas the water footprint is the volume (in m³ yr^{−1}) of freshwater required¹². The ecological footprint directly defines the ecological impact of human consumption by comparing the available bioproductive area to the area required for the consumption of specific goods and services. The water footprint tracks the volume of virtual water used by a population, where virtual water is the volume of freshwater used to produce a commodity, good or service along the various steps of production^{13,14,17}. The water footprint quantifies the components of virtual water: green water (soil water), blue water (surface water and groundwater) and grey water (polluted water). However, until recently¹⁸ the water footprint was not able to assess the impact of our water consumption on natural stocks and flows¹⁹ because it generally focused on the volumes of water required without quantifying the volume of water available. The groundwater footprint, as proposed here, is complementary to the well-established water footprint method and can be used to assess the impact of our groundwater consumption on natural stocks and flows. Here, we apply the groundwater footprint methodology globally to regional-scale, hydrologically active aquifers²⁰ (see Supplementary Information for a definition). The focus of the method is currently on groundwater quantity rather than

quality, which is a conservative assumption that results in smaller groundwater footprints for aquifers affected by groundwater contamination. The groundwater footprint method can be applied to a variety of scales and contexts like the ecological footprint, water footprint and virtual water concepts^{12–14}.

We define the groundwater footprint as the area required to sustain groundwater use and groundwater-dependent ecosystem services of a region of interest, such as an aquifer, watershed or community. The groundwater footprint (GF) is defined more formally as $GF = A[C/(R - E)]$, where C , R and E are respectively the area-averaged annual abstraction of groundwater, recharge rate, and the groundwater contribution to environmental streamflow, all in units with dimensions of length/time, such as m d^{−1} (Supplementary Fig. 1). A (in units of length², such as m²) is the areal extent of any region of interest where C , R and E can be defined. The groundwater footprint is essentially a water balance between aquifer inflows (R) and outflows (C and E) which can be derived from observations and/or model output. C is derived directly from the use of groundwater at the scale of interest although actual groundwater abstraction is often poorly known^{9,11}. R is the long-term natural areal flux into the system plus the additional recharge from irrigation, and can be derived from geochemical tracer methods or hydrologic models^{21,22}. E is the quantity of groundwater that needs to be allocated to surface water flow to sustain ecosystem services, which is most important during low flow conditions^{23,24}. Thus, the groundwater footprint method emphasizes the contribution of groundwater to the environmental requirements during low flows, although natural streamflow variability is also essential to maintaining the environmental integrity of surface water systems²⁵. Environmental flow requirements for specific aquifers or watersheds are most accurately determined by detailed hydroecological data and multidisciplinary expert consultation at the scale of specific aquifers or watersheds^{24,25}. The Supplementary Information contains the mathematical relationship of the groundwater footprint to the ecological footprint¹⁶ and previous water stress indicators^{4–6,24}, as well as other forms of the groundwater footprint equation that may be useful for local calculations with different data sources.

We calculated the global groundwater footprint as the sum of the groundwater footprints of large aquifers worldwide using spatially distributed recharge rates and environmental flows derived from PCR-GLOBWB and gridded groundwater consumption estimates²⁶ (see Methods Summary and Fig. 1). PCR-GLOBWB is a conceptual, process-based global hydrologic model that simulates the daily water balance for 1958–2000 at 0.5° resolution (that is, ~50 km at the Equator) and is validated to GRACE satellite observations and global streamflow estimates^{10,22,26}. Recharge (R) is the long-term natural groundwater recharge and additional recharge from irrigation derived from ref. 10. For global-scale assessment of water resources, low flow requirements based on consistent hydrologic criteria are useful¹⁷. Therefore, following ref. 24, environmental flows (E) were taken to be equal to Q_{90} , the monthly streamflow that is exceeded 90% of the time during the period 1958–2000. We calculated environmental flows

¹Department of Civil Engineering, McGill University, Montreal, Quebec H3A 0C3, Canada. ²Department of Physical Geography, Faculty of Geosciences, Utrecht University, PO Box 80115, 3508 TC Utrecht, The Netherlands. ³Deltares, PO Box 85467, 3508 AL Utrecht, The Netherlands.

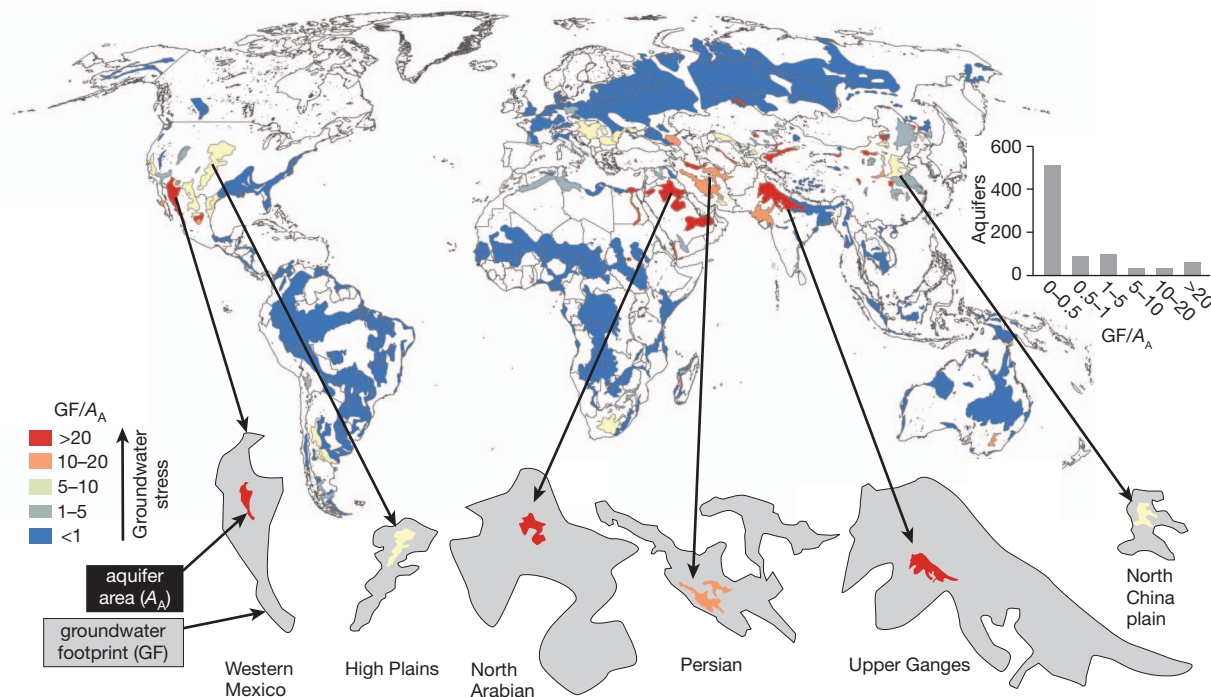


Figure 1 | Groundwater footprints of aquifers that are important to agriculture are significantly larger than their geographic areas. Aquifers are major groundwater basins with recharge of $>2 \text{ mm yr}^{-1}$ in the global inventory of groundwater resources²⁰ (see Supplementary Information). At the bottom of the figure, the areas of the six aquifers (Western Mexico, High Plains, North

Arabian, Persian, Upper Ganges and North China plain) are shown at the same scale as the global map; the surrounding grey areas indicate the groundwater footprint proportionally at the same scale. The ratio GF/A_A indicates widespread stress of groundwater resources and/or groundwater-dependent ecosystems. Inset, histogram showing that GF is less than A_A for most aquifers.

at the basin scale and the associated groundwater requirement expressed as a uniform fraction of total recharge (see Methods Summary and Supplementary Fig. 2). This basin-scale fraction was then multiplied with the grid-based recharge to obtain E . We derived grid-based groundwater abstraction, C , for the year 2000 (ref. 26; see Supplementary Information) and subsequently aggregated the fluxes C , R and E over hydrologically active regional aquifers²⁰ to calculate their groundwater footprint. Aggregation at the scale of regional aquifers is justifiable given the resolution of the input data while naturally integrating lateral groundwater flow that might occur due to abstraction wells.

Figure 1 is, to our knowledge, the first spatially explicit comparison of groundwater use, availability and environmental flow for aquifers globally. We acknowledge that each of the regional aquifers has significant internal heterogeneity and that groundwater extractions

often acutely affect smaller regions within aquifers, although we partly account for this heterogeneity by using the highest available resolution of regional aquifers²⁰ as the basis for aggregation. A few aquifers with well-documented histories of groundwater depletion have large groundwater footprints (for example, the Upper Ganges, High Plains, North China plain and Central Valley^{7,8,27,28}; Table 1). A number of other aquifers with large groundwater footprints (for example, the Persian, Arabian and Western Mexico aquifers) are not as well documented, although evidence of groundwater depletion in these aquifers is discussed in non-peer-reviewed literature (see Supplementary Information). It is instructive to compare the ratio of groundwater footprint (GF) to aquifer area (A_A), which is a groundwater stress indicator (see Supplementary Information). $\text{GF}/A_A > 1$ indicates where unsustainable groundwater consumption could affect groundwater availability and groundwater-dependent surface water

Table 1 | Properties of aquifers with the largest groundwater footprints

Aquifer	Country	GF (10^6 km^2)	A_A (10^6 km^2)	GF/A_A
Upper Ganges	India, Pakistan	26.1 ± 7.5	0.48	54.2 ± 15.6
North Arabian	Saudi Arabia	17.3 ± 4.7	0.36	48.3 ± 13.5
South Arabian	Saudi Arabia	9.5 ± 3.6	0.25	38.5 ± 14.7
Persian	Iran	8.4 ± 3.7	0.42	19.7 ± 8.6
South Caspian	Iran	5.9 ± 2.0	0.06	98.3 ± 32.6
Western Mexico	Mexico	5.5 ± 2.0	0.21	26.6 ± 9.4
High Plains	USA	4.5 ± 1.2	0.50	9.0 ± 2.4
Lower Indus	India, Pakistan	4.2 ± 1.5	0.23	18.4 ± 6.5
Nile delta	Egypt	3.1 ± 0.8	0.10	31.7 ± 7.9
Danube basin	Hungary, Austria, Romania	2.4 ± 0.8	0.32	7.4 ± 2.6
Central Mexico	Mexico	1.8 ± 0.5	0.20	9.1 ± 2.6
North China plain	China	1.8 ± 0.6	0.23	7.9 ± 2.8
Northern China	China	1.4 ± 0.6	0.31	4.5 ± 1.8
North Africa	Algeria, Tunisia, Libya	0.9 ± 0.3	0.36	2.6 ± 0.9
Central Valley	USA	0.4 ± 0.2	0.07	6.4 ± 2.4
Other aquifers		38.6 ± 10.8	34.17	1.1 ± 0.3
All aquifers		131.8 ± 24.9	38.27	3.5 ± 0.7

The values of GF (groundwater footprint) and GF/A_A are the mean and standard deviation of 10,000 Monte Carlo realizations based on independent estimates of recharge and abstraction¹⁰. Note that only the 15 aquifers with the largest GF are listed individually. The remaining 768 'other aquifers' are included in 'all aquifers'. GF/A_A is calculated before rounding the GF to one decimal place. A_A is aquifer area.

and ecosystems. The ratio GF/A_A is $\gg 1$ for the aquifers with large groundwater footprints mentioned above, indicating unsustainable groundwater mining, often of fossil groundwater recharged under past climatic conditions (Table 1). However, the majority of aquifers in the world have $GF < 10^6 \text{ km}^2$ and 80% of aquifers have $GF/A_A < 1$, suggesting that groundwater depletion is not ubiquitous (Fig. 1).

The size of the global groundwater footprint is currently $(131.8 \pm 24.9) \times 10^6 \text{ km}^2$, or 3.5 ± 0.7 times the actual area of hydrologically active aquifers²⁰. Even if no groundwater is allocated for environmental flows ($E = 0$), the global groundwater footprint is still $(76.5 \pm 15.7) \times 10^6 \text{ km}^2$ or 2.0 ± 0.4 times the actual aquifer area (Supplementary Table 2). The global groundwater footprint is dominated by a handful of countries, including the United States, China, Pakistan, Iran, India, Mexico and Saudi Arabia (Table 1). The ratio of global groundwater consumption to the difference between global recharge and global environmental streamflow is ~ 0.2 . High recharge rates in some ecologically sensitive areas, such as the Amazon, are included in this calculation but practically cannot be used to balance overexploitation in arid regions. 1.7 ± 0.4 billion people live in regions with $GF/A_A > 1$, where groundwater consumption could affect groundwater availability and/or groundwater-dependent surface water and ecosystems in the future. Approximately 60% of the people²⁹ living in regions with $GF/A_A > 1$ are located in India and China (Fig. 2a).

The groundwater footprint can be used to assess the potential to increase agricultural yields with renewable groundwater, or can be combined with water footprint and virtual water calculations. Foley *et al.*¹⁵ 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. Crop yields may be limited by a number of factors, including water or nutrient availability and management¹⁵, but increasing agricultural yields generally leads to increased water demand. Because groundwater is critical for irrigation in many agricultural regions, it is useful to assess how the spatial distribution of groundwater stress (Fig. 1) compares to the potential for new calories (figure 3 in ref. 15). Figure 2b shows that some areas with potential new calories coincide with aquifers that are less stressed, suggesting there is potential that renewable groundwater could be used sustainably to increase crop yields. However, aquifers that are significantly stressed ($GF/A_A \gg 1$) also underlie areas with potential new calories, and in these regions groundwater cannot be used sustainably to increase yields. These analyses only consider the groundwater footprint and agricultural yields, and should be placed in a broader socio-economic context.

We now show how the groundwater footprint can be used to assess the impact of transferring groundwater consumption between regions: the Upper Ganges aquifer in northwestern India and Pakistan has the largest groundwater footprint and a large GF/A_A ratio (Table 1), but the Lower Ganges aquifer has a GF/A_A ratio of less than one owing to low groundwater consumption and high recharge rates (Supplementary Fig. 3). Transferring even a small percentage of the groundwater consumption of the Upper Ganges to the Lower Ganges leads to a significant decrease in the combined groundwater footprint and GF/A_A ratio, because the aquifer-scale recharge rate to the Lower Ganges aquifer is approximately ten times higher than to the Upper Ganges aquifer (Supplementary Fig. 3). However, even if all the groundwater consumption of the Upper Ganges is transferred, the combined GF/A_A ratio remains greater than one, indicating that the current groundwater consumption in the region cannot be made sustainable by transferring groundwater consumption. In the future, the groundwater footprint could potentially serve as a metric to assess to what extent renewable groundwater could be exploited in virtual water trade schemes.

We stress that all variables used in our calculations, except for area, are subject to uncertainty. Least known are the environmental flow requirements, which are dependent on expert consultation and

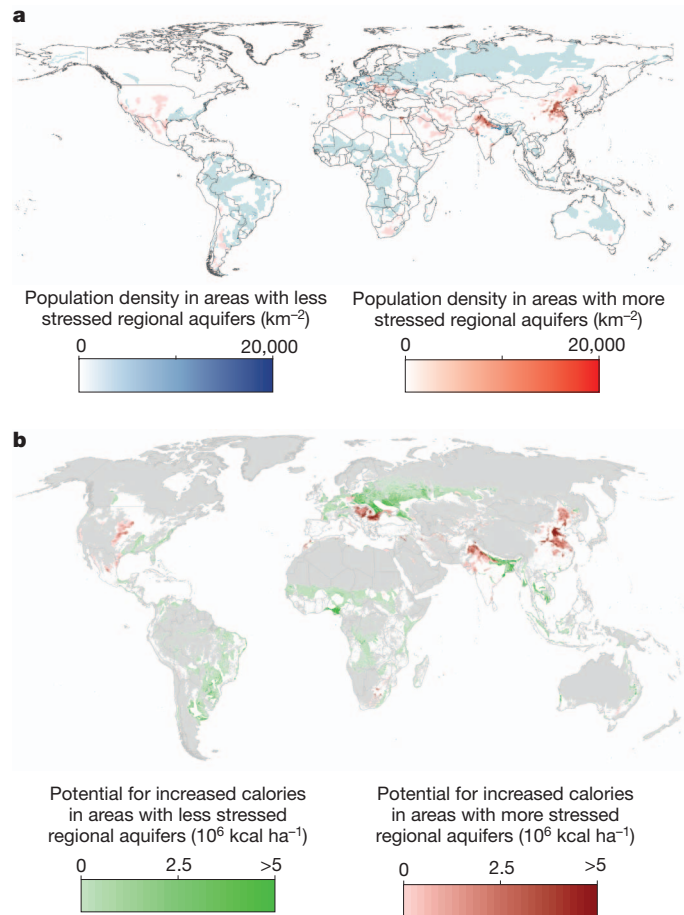


Figure 2 | Groundwater stress may be affecting ~ 1.7 billion people and could limit the potential to increase agricultural production. The ratio GF/A_A is used to differentiate areas with less groundwater stress ($GF/A_A < 1$) and more groundwater stress ($GF/A_A > 1$). **a**, Population densities, derived from the gridded population of the world for year 2000 (ref. 29). Areas that do not have underlying regional aquifers, or that have very low population density are shown in white. **b**, Potential for increased calories (see main text). Some areas with potential new calories¹⁵ coincide with stressed aquifers and some areas coincide with aquifers that are less stressed. Areas with potential new calories that are not underlain by a regional aquifer are shown in white.

detailed hydroecological relationships that are often poorly defined. However, in our global calculations we kept the environmental flow conditions constant, as it is primarily a management decision at regional to national scales and we explicitly incorporated the uncertainty due to recharge and groundwater consumption using a Monte Carlo analysis with 10,000 realizations (see Methods Summary). In the future, other data sets, including sub-national groundwater consumption data (Supplementary Fig. 4), could be used, where available, to calculate the groundwater footprint at different scales or for different administrative units.

The groundwater footprint is a powerful and hydrologically grounded tool for groundwater analysis and policy that complements and extends the ecological footprint, water footprint and virtual water methods. It is an advance on previous work on groundwater depletion^{6–8} as it explicitly includes environmental flows, it considers aquifers as a hydrologically grounded scale of analysis, it is more intuitive to water managers and the general public than depletion volumes, and it is based on improved estimates of recharge and abstraction. As exemplified above, the groundwater footprint refocuses the discussion to solutions, making it a valuable water management and policy tool. Practically, it allows short-term water resource monitoring and management measures to focus on the handful of aquifers with egregious groundwater footprints rather than dissipating

efforts across all aquifers. Additionally, the groundwater footprint can be used to assess the potential to achieve increased agricultural yields with sustainable groundwater. Also, as satellite-based groundwater depletion data sets (GRACE) are emerging^{7,8}, the groundwater footprint offers a useful framework for analysing these global depletion data sets in a broader framework of groundwater resource use, availability and environmental flows. Last, because the groundwater footprint method is flexible and spatially distributed, it could be modified for other resources whose renewal is slow and spatially heterogeneous, such as fisheries, forestry or soil.

METHODS SUMMARY

Global, spatially distributed estimates of the recharge rate, R , were obtained from the hydrological model PCR-GLOBWB²² using a global permeability map³⁰. Annual fields were averaged⁹ to obtain the average recharge rate over the period 1958–2000 with a spatial resolution of 0.5°. Artificial recharge due to irrigation water was added¹⁰. In the absence of global information on environmental flow requirements, the monthly streamflow exceeded 90% of the time (Q_{90}) was adopted²². Per basin, Q_{90} was determined at the basin outlet for the entire simulation period. A basin-wide uniform fraction was computed by which the groundwater recharge contributes to the environmental flow requirement E . Grid-based annual groundwater abstraction, C , was derived from reported country statistics for the year 2000 (<http://www.un-igrac.org>), which were downscaled spatially relative to the local surface water deficit or total water demand depending on the situation per country²⁶. The above quantities of R , E and C were aggregated over hydrologically active, regional aquifers²⁰ to compute the aquifer-scale groundwater footprint. To account for uncertainty, we made use of the uncertainty estimates for recharge and groundwater abstraction of ref. 9. E was excluded from the uncertainty analysis, as it is often defined a priori as a management decision at regional to national scales. Following ref. 9, a Monte Carlo simulation with 100 independent realizations of R and C returned 10,000 values for the groundwater footprint for the hydrologically active aquifers, from which the mean and standard deviation were computed. The groundwater footprints were (1) summed globally to compare to the actual aquifer area, (2) used to calculate the affected population numbers using the gridded global population for year 2000 (ref. 29) and (3) compared to the spatial distribution of potential new calories¹⁵. See Supplementary Information for details on methods and data sets, as well for additional validation, including regional groundwater abstraction (Supplementary Fig. 4 and Supplementary Table 3).

Received 28 February; accepted 1 June 2012.

- Giordano, M. Global groundwater? Issues and solutions. *Annu. Rev. Environ. Resour.* **34**, 153–178 (2009).
- Siebert, S. *et al.* Groundwater use for irrigation — a global inventory. *Hydrol. Earth Syst. Sci.* **14**, 1863–1880 (2010).
- Postel, S. L., Daily, G. C. & Ehrlich, P. R. Human appropriation of renewable fresh water. *Science* **271**, 785–788 (1996).
- Vorosmarty, C. J., Green, P., Salisbury, J. & Lammers, R. B. Global water resources: vulnerability from climate change and population growth. *Science* **289**, 284–288 (2000).
- Alcamo, J. *et al.* Global estimates of water withdrawals and availability under current and future business-as-usual conditions. *Hydrol. Sci. J.* **48**, 339–348 (2002).
- Oki, T. & Kanae, S. Global hydrological cycles and world water resources. *Science* **313**, 1068–1072 (2006).
- Rodell, M., Velicogna, I. & Famiglietti, J. S. Satellite-based estimates of groundwater depletion in India. *Nature* **460**, 999–1002 (2009).
- Famiglietti, J. S. *et al.* Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophys. Res. Lett.* **38**, L03403, <http://dx.doi.org/10.1029/2010GL046442> (2011).
- Wada, Y. *et al.* Global depletion of groundwater resources. *Geophys. Res. Lett.* **37**, L20402, <http://dx.doi.org/10.1029/2010GL044571> (2010).
- Wada, Y., van Beek, L. P. H. & Bierkens, M. F. P. Nonsustainable groundwater sustaining irrigation: a global assessment. *Wat. Resour. Res.* **48**, W00L06, <http://dx.doi.org/10.1029/2011WR010562> (2012).
- Konikow, L. F. Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophys. Res. Lett.* **38**, L17401, <http://dx.doi.org/10.1029/2011GL048604> (2011).
- Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M. & Mekonnen, M. M. *The Water Footprint Assessment Manual: Setting the Global Standard* (Earthscan, 2011).
- Hoekstra, A. Y. Human appropriation of natural capital: a comparison of ecological footprint and water footprint analysis. *Ecol. Econ.* **68**, 1963–1974 (2009).
- Allan, J. A. Virtual water: a strategic resource, global solutions to regional deficits. *Ground Water* **36**, 545–546 (1998).
- Foley, J. A. *et al.* Solutions for a cultivated planet. *Nature* **478**, 337–342 (2011).
- Wackernagel, M. & Rees, W. *Our Ecological Footprint* (New Society Publishers, 1996).
- Hoekstra, A. Y. & Mekonnen, M. M. The water footprint of humanity. *Proc. Natl Acad. Sci. USA* <http://dx.doi.org/10.1073/pnas.1109936109> (published online, 13 February 2012).
- Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E. & Richter, B. D. Global monthly water scarcity: blue water footprints versus blue water availability. *PLoS ONE* **7**, e32688 (2012).
- Hoekstra, A. Y., Gerbens-Leenes, W. & van der Meer, T. H. Reply to Pfister and Hellweg: Water footprint accounting, impact assessment, and life-cycle assessment. *Proc. Natl Acad. Sci. USA* **106**, E114 (2009).
- BGR/UNESCO. Groundwater Resources of the World 1 : 25 000 000 http://www.whymap.org/whymap/EN/Products/products_node_en.html (2008).
- Döll, P. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environ. Res. Lett.* **4**, 035006 (2009).
- van Beek, L. P. H., Wada, Y. & Bierkens, M. F. P. Global monthly water stress: 1. Water balance and water availability. *Wat. Resour. Res.* **47**, W07517 (2011).
- Smakhtin, V. U. Low flow hydrology: a review. *J. Hydrol.* **240**, 147–186 (2001).
- Smakhtin, V. U., Revenga, C. & Döll, P. A pilot global assessment of environmental water requirements and scarcity. *Wat. Int.* **29**, 307–317 (2004).
- Poff, N. L. *et al.* The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwat. Biol.* **55**, 147–170 (2010).
- Wada, Y. *et al.* Global monthly water stress: 2. Water demand and severity of water stress. *Wat. Resour. Res.* **47**, W07518 (2011).
- Sophocleous, M. Review: groundwater management practices, challenges, and innovations in the High Plains aquifer, USA — lessons and recommended actions. *Hydrogeol. J.* **18**, 559–575 (2010).
- Foster, S. *et al.* Quaternary Aquifer of the North China Plain—assessing and achieving groundwater resource sustainability. *Hydrogeol. J.* **12**, 81–93 (2004).
- CIESIN. *Gridded Population of the World Version 3 (GPWv3): Population Density Grids* (Socioeconomic Data and Applications Center (SEDAC), Columbia University, 2011); available at <http://sedac.ciesin.columbia.edu/gpw> (accessed, 17 February 2011).
- Gleeson, T. *et al.* Mapping permeability over the surface of the Earth. *Geophys. Res. Lett.* **38**, L02401, <http://dx.doi.org/10.1029/2010GL045565> (2011).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements S. Siebert, M. Jellinek, M. Lathuilliere, A. Henderson and W. Rees read or discussed earlier versions of the manuscript, which markedly improved it. T.G. was supported by the Natural Sciences and Engineering Research Council of Canada and a Canadian Institute for Advanced Research junior fellowship. Y.W. was supported by Utrecht University Focus Areas Theme ‘Earth and sustainability’.

Author Contributions T.G. developed the groundwater footprint method, created the figures and wrote the paper with input from all authors. Y.W. and L.P.H.v.B. completed the analysis of groundwater consumption and hydrologic data. L.P.H.v.B., T.G. and M.F.P.B. developed the environmental flow methodology. All authors discussed results and edited the paper.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of this article at www.nature.com/nature. Correspondence and requests for materials should be addressed to T.G. (tom.gleeson@mcgill.ca).