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Model estimates of sea-level change due to anthropogenic impacts on terrestrial water storage

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Global sea level has been rising over the past half century, according to tide-gauge data[1,2]. Thermal expansion of oceans, melting of glaciers and loss of the ice masses in Greenland and Antarctica are commonly considered as the largest contributors, but these contributions do not entirely explain the observed sea-level rise[1]. Changes in terrestrial water storage are also likely to affect sea level[3–6], but comprehensive and reliable estimates of this contribution, particularly through human water use, are scarce[1]. Here, we estimate sea-level change in response to human impacts on terrestrial water storage by using an integrated model that simulates global terrestrial water stocks and flows (exclusive to Greenland and Antarctica) and especially accounts for human activities such as reservoir operation and irrigation. We find that, together, unsustainable groundwater use, artificial reservoir water impoundment, climate-driven changes in terrestrial water storage and the loss of water from closed basins have contributed a sea-level rise of about 0.77 mm yr^{-1} between 1961 and 2003, about 42% of the observed sea-level rise. We note that, of these components, the unsustainable use of groundwater represents the largest contribution.

Global sea-level change (SLC) is widely debated[3–10] because it is affected by numerous natural and anthropogenic factors such as thermal expansion of the oceans, melting of glaciers associated with global warming and change in terrestrial water storage (TWS) including soil water, groundwater, snow and surface water in natural lakes and artificial reservoirs. Tide-gauge-based observations indicate that the global sea level rose by ~ 1.8 mm yr^{-1} over the second half of the twentieth century[1,2]. The total contribution of climate-related factors (thermal expansion of oceans, glaciers and ice caps melting, and loss of ice masses in Greenland and Antarctica) has been estimated to be $\sim$1.1 mm yr^{-1} (refs 1,11–14), which leaves an unaccounted SLC of $\sim$0.7 mm yr^{-1}. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) concluded that the budget of sea-level rise has not yet been closed satisfactorily, primarily owing to the large uncertainties in the contributions of anthropogenic TWS variations[1] (for example, artificial reservoir water impoundment, groundwater depletion). More recent literature has affirmed the significance of these anthropogenic impacts[3,5,15].

Among the two most significant anthropogenic impacts, artificial reservoirs have caused a drop in the sea level by impounding a significant amount of water over land (with the global capacity of $>$8,000 km^3; ref. 16); and by contrast, unsustainable groundwater use[17–19] (groundwater depletion) has contributed to sea-level rise because a large portion of the water removed from the groundwater systems ultimately reaches the oceans[20]. Some studies have estimated the individual contributions of reservoir impoundment[4] and groundwater depletion[19,21] to SLC. These studies have estimated the contribution of reservoir impoundment based on the maximum storage capacity (assuming that all reservoirs considered are 85% filled) rather than by estimating the actual storage variations[4], and that of groundwater depletion by using region-specific data sets without accounting for the changes in other TWS components owing to groundwater abstraction[19,21]. Although a few other studies have provided more comprehensive estimates of the contributions of various TWS components[8,20], they are based on the water balance computations. Therefore, comprehensive and reliable estimates of SLC owing to changes in TWS, particularly through human water use, are still scarce.

Here, we use an integrated water resources assessment model[17] to provide a comprehensive estimate of the contribution to SLC due to TWS variations caused by various anthropogenic factors. Although this modelling study mainly focuses on the contributions of artificial reservoirs and unsustainable groundwater use to SLC, other climate-driven factors associated with TWS variations are also considered. Furthermore, we investigate the critical issue as to whether the anthropogenic TWS contribution to SLC can partially fill the large gap in the sea-level budget reported by the AR4. The integrated model used here was developed by incorporating various anthropogenic water regulation modules (for example, reservoir operation, irrigation, withdrawal and environmental flow requirements) into a land surface model (LSM) in a consistent manner (see Methods and ref. 17).

As reservoir storage is one of the main components investigated here, we evaluate model simulations by comparing them with the available observations to demonstrate that the results obtained are robust and reliable. Comparison of the simulated TWS anomaly (TWSA) against the measurements from the Gravity Recovery and Climate Experiment satellite mission[22] over the highly regulated river basins (see Supplementary Information) indicates that accounting for artificial reservoir storage improves the TWS simulations (Supplementary Figs S1–S4) in most of the highly regulated basins. The operation schemes of some reservoirs,

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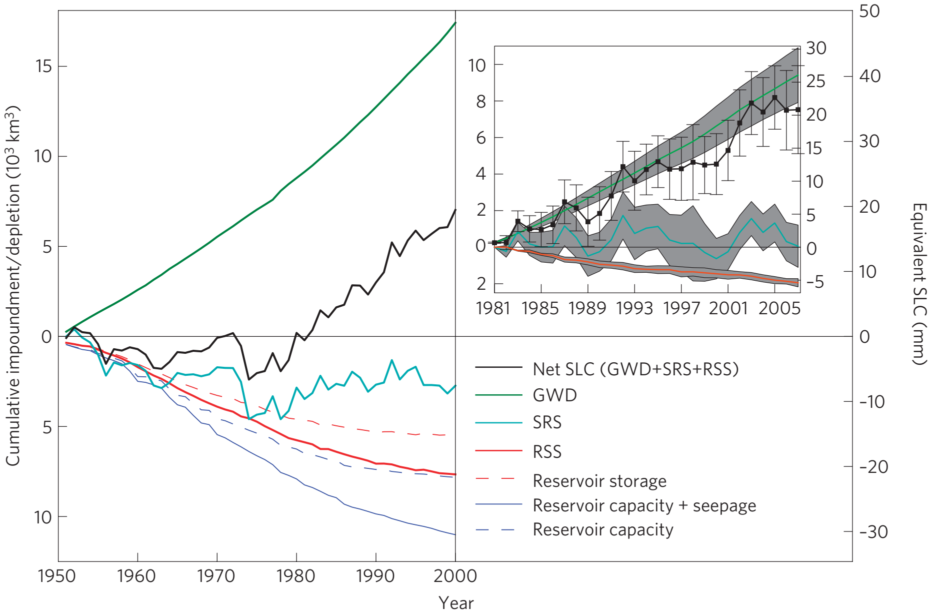

Figure 1 | The terrestrial water storage contributions to sea-level change. Soil, river and snow water contributions (shown as the relative water storage to the initial storage) account for climate-driven TWS variation and change in soil water due to irrigation, but the contribution of artificial reservoir storage has been deducted. The inset shows the results based on four different precipitation data sets for the period 1981–2007. The grey shading indicates the uncertainty in SLC (±two standard deviations). For clarity, the uncertainty in the net SLC is shown by error bars. GWD, groundwater depletion; SRS, soil, river and snow water; RSS, reservoir storage and seepage.

such as Lake Powell (USA), Navajo (USA) and Sirikit (Thailand), have been demonstrated to capture the observed reservoir storage variation well[23]. We revisited this evaluation and confirmed that the integrated model simulates the mean annual reservoir storage fairly well (Supplementary Fig. S5).

Pokhrel *et al.*[17] showed that the incorporation of anthropogenic water regulation modules in the model significantly improves river discharge simulations over the highly regulated river basins. For the less-regulated basins, the model also simulates observed TWSA well (see Fig. 2 of refs 17 and 24). Moreover, our investigation shows that the representation of reservoir storage in the model improves TWSA simulations in many basins, such as the Angara, Churchill and Sao Francisco basins (Supplementary Fig. S2). These evaluations support the use of the integrated model for estimating the contribution of TWS variation to SLC.

Figure 1 plots the cumulative contribution of various TWS components to SLC from 1951 to 2000 based on the NCC–HI simulation (that is, a simulation using NCC (ref. 25) forcing, with all the human impact (HI) schemes turned on; see Methods). In the following, the reported maximum reservoir capacity and simulated actual storage are termed as capacity and storage, respectively. Averaged over the global ocean area (3.61×10^8 km^2), the 1951–2000 cumulative contributions of reservoir capacity and reservoir storage to sea-level drop are ∼ 22 and ∼15 mm, respectively. The large difference between the capacity and storage contributions is reasonable because reservoir storage changes significantly between wet and dry seasons. Averaged annually, our results indicate that large reservoirs are ∼70% filled when the maximum storage is targeted at 85% (ref. 23), with significant interannual variations ranging from 60 to 85% of the capacity. When the seepage from reservoirs is considered (see Methods), the cumulative contributions of reservoir capacity and reservoir storage are ∼31 and ∼21 mm, respectively. Again, note the large difference (10 mm) between the contribution based on the maximum storage capacity of reservoirs (also see ref. 4) and the simulated actual storage.

The simulated mean annual unsustainable groundwater use during 1951–2000 is ∼359 km^3 yr^{-1}. Therefore, following the assumption that 97% of unsustainable groundwater use ends up in the oceans[19], the cumulative sea-level rise is ∼48 mm. We also find that the net contribution of climate-driven TWS changes (soil moisture, snow and river storage; exclusive of Greenland and Antarctica) to SLC during 1951–2000 is ∼8 mm (Fig. 1), which is higher than the reported values[6,10]. Note that soil water storage accounts for the increased soil water content owing to irrigation. As Fig. 1 shows, although the climate-driven TWS variation has notable interannual and decadal fluctuations, the long-term effects are rather small compared with those of other TWS components, consistent with the findings of previous studies[6,10].

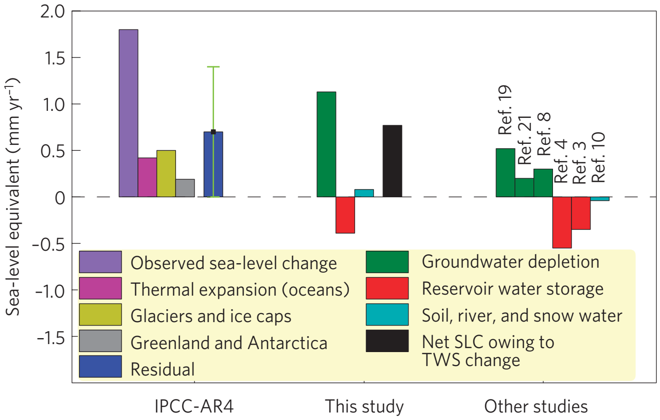

Figure 2 | Estimates of various contributions to the observed SLC. The estimates of the IPCC AR4 and that of this study are for the period 1961–2003, whereas the estimates of the other studies are for the later half of the twentieth century, except for Wada *et al.*[19] (1960–2000). Error bar indicates the uncertainty range in the residual of the sea-level budget estimated by the AR4. Note that the results of Chao *et al.*[4] include seepage loss from reservoirs but that of Lettenmaier and Milly[3] do not include this loss.

Irrigation also affects SLC due to the net water loss from the irrigated systems through increased consumptive water use, particularly in the endorheic water bodies such as the Aral Sea. We find that the net decrease in the inflow to the Aral Sea resulting from water diversion for irrigation from the two main rivers feeding this sea (Amu Darya and Syr Darya) is $\sim$500 km^3 ($\sim$1.4 mm of SLC). In line with a conclusion of the previous study[8], our result indicates that the water loss from other large endorheic water bodies (for example, the Caspian Sea) is relatively small. Therefore, the net effect of irrigation-induced water loss from the endorheic basins is rather small.

The uncertainty in the estimation of TWS contribution to SLC caused by using different global-precipitation-forcing data sets is evaluated. The inset in Fig. 1 presents the TWS contribution to SLC (1981–2007) when four global precipitation data sets were used to force the model (see Methods for details). The shading in this plot denotes the uncertainty quantified as twice the standard deviation of the four simulations. As seen, various precipitation data cause a significant uncertainty in the simulated TWS and unsustainable groundwater use. The net contribution of TWS to SLC for the period 1981–2007 is $+20.8 \pm 6.7$ mm (groundwater $+26.1 \pm 4.1$, climate-driven TWS $+0.1 \pm 3.2$ and reservoir storage -5.4 ± 0.6 mm). Therefore, the uncertainty in the net TWS contribution to SLC owing to precipitation forcing can be as high as 30%.

To compare our results of net SLC with the reported gap in the sea-level budget estimated by the AR4, we estimate the net SLC for the period of 1961–2003 (see Methods). As summarized in Fig. 2, the net contribution to SLC is $+0.77$ mm yr^{-1} (groundwater $+1.05$, climate-driven TWS $+ 0.08$, reservoir storage -0.39 and the Aral Sea $+0.03$), which explains $\sim$42% of the observed sea-level rise and is comparable to the unexplained SLC ($+0.70$ mm yr^{-1}) estimated by the AR4 (ref. 1). Also shown in the figure are the individual contributions of thermal expansion of the oceans ($\sim$0.42; refs 11, 12), glaciers and ice caps melting ($\sim$0.5; refs 13,14), and loss of ice masses in Greenland and Antarctica ($\sim$0.19 mm yr^{-1}; refs 1,14). As seen in the inset of Fig. 1, the recent higher TWS contribution to SLC is mainly the result of increased groundwater use and larger climate-driven TWS change, with the latter being highly forcing-dependent. Moreover, as reservoir water impoundment has levelled off in recent years, the compensating effect on sea-level rise has decreased. By contrast, the contribution of groundwater depletion has been increasing monotonously and may continue to do so in the future, which will heighten the concerns regarding the potential sea-level rise in the twenty-first century. Compared with groundwater withdrawal, the climate-driven TWS change makes a smaller contribution to SLC in the long term, but this estimate is highly sensitive to the precipitation data set used.

We note that even though this study is based on a state-of-the-art model that has been validated extensively, certain modelling assumptions could have added an extent of uncertainty to our results (see the discussion in ref. 17). In particular, our estimation of unsustainable groundwater use is higher than the existing estimates[19], possibly because groundwater is withdrawn unlimitedly until the total demand is fulfilled, an assumption made mainly owing to the lack of global data sets on the availability of groundwater sources. Nevertheless, model results are within the plausible limits for many countries using large amounts of groundwater[17]. Some other studies[21,26] have estimated a smaller amount of global groundwater depletion, but these studies have used methodologies different from the integrated modelling approach used here. For example, the estimate of Wada *et al.*[19], limited to arid and semi-arid regions, was based on the data of groundwater withdrawal and modelled recharge. In contrast, Konikow[21] applied a number of different methodologies to calculate groundwater depletion in different regions. Therefore, significant discrepancies exist among different estimates of groundwater depletion. Furthermore, it is not clear whether all the mined groundwater (97–100%; refs 19,21) eventually ends up in the oceans, as some of the irrigation groundwater may cause changes in other storage components, such as soil moisture, on local or regional scales. Such effects have been partially accounted for in our global model. Thus, improving model simulations with an explicit representation of dynamic groundwater and pumping schemes, and its interactive coupling with climate model simulations will help to provide a more accurate estimation of the contribution of unsustainable groundwater use to SLC.

Several other factors that potentially affect SLC (for example, wetland drainage, change in the atmospheric water content) are not considered here. However, all these factors have relatively smaller contributions to SLC (refs 8,15). The effects of deforestation and urbanization are partially included by using the time-varying land-use-change data sets. Despite these limitations, we have provided a comprehensive estimate of the contributions of anthropogenic and climate-driven TWS variation to SLC using a state-of-the-art integrated modelling framework that accounts for the main human impacts on the global terrestrial water cycle. Our results suggest that the anthropogenic TWS contributions to SLC are significant, with groundwater being a major contributor to the observed sea-level rise. The net anthropogenic TWS contribution to SLC could potentially fill the gap in the sea-level budget which, according to AR4, has not yet been closed satisfactorily.

Methods

The model used here is an integrated water resources assessment modelling framework[17], the core of which is an LSM, the Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO; ref. 27). A river-routing scheme[28] and human-impacts schemes (reservoir operation, irrigation, withdrawal and environmental flow requirements) have recently been incorporated within the LSM (see Supplementary Methods for details). A detailed description of the reservoir operation scheme is provided by ref. 23 and the incorporation of various modules into MATSIRO and its model evaluation can be found in ref. 17.

Owing to the lack of detailed information on the global scale, we estimate the number of years required to fill the reservoirs simply as $NYR_{\text{fill}} = \alpha \times S/I$, where α is a dimensionless constant set to 0.85 (see ref. 23) and $S(L^3)$ and $I(L^3)$ are the reservoir capacity and mean annual inflow to the reservoir, respectively. In the simulation, reservoirs begin to impound water NYR_{fill} years before the year of reservoir completion. Seepage from reservoirs, which may vary considerably for individual reservoirs depending on the local geology and climate conditions, potentially leads to a significant amount of water loss to the adjacent aquifers that manifests as water table rise in nearby areas[4]. As no detailed information is available globally, we assume that 5% (ref. 4) of the reservoir storage is lost through seepage in the initial year of reservoir completion and this rate decreases as $1/\sqrt{t}$ in the succeeding years; therefore, the total water seepage grows slowly as $\sqrt{t}$, where t is the number of years since the completion of the reservoir[4]. Thus, the cumulative contribution of seepage to SLC is estimated by integrating the total seepage over time.

Unsustainable groundwater use is estimated based on the total water demand (domestic, industrial and agricultural) and the availability of water from near-surface sources. This approach proposed by previous studies[29,30] estimates the unsustainable groundwater use implicitly, as the model does not explicitly account for groundwater dynamics. Water is withdrawn unlimitedly when needed because there are no global data sets on the availability of groundwater sources. Nevertheless, it has been shown that the model-estimated global and country-scale groundwater depletion is within the range of the reported statistics for circa 2000 (ref. 17).

Six-hourly atmospheric forcing data are obtained from two different sources[24,25]. Land-surface properties, including land cover, soil type and associated model parameters, are the same as used by Pokhrel *et al.*[17] or follow the default values of Takata and colleagues[27]. Data for historical land-use change, cropland areas and irrigated areas are compiled from various sources (see Supplementary Methods). Large and medium-sized reservoir capacities are taken from the International Commission on Large Dams[16] (see Supplementary Methods). The global total reservoir capacity of the data used here, including large and medium-sized reservoirs, is $\sim$8,000 km^3 ($\sim$95% of the documented global capacity; ref. 4). Agricultural water requirement is simulated based on the soil moisture deficit during the cropping season for 19 different crop types[17], whereas the data for domestic and industrial water use are obtained from the AQUASTAT database of the Food and Agricultural Organization (FAO) of the United Nations. Historical (annual) data for domestic and industrial water use are obtained by scaling the data for the year 1995 by the rate of increase in population.

A series of global simulations is carried out at the 1° × 1° resolution. First, three simulations, namely the Global Precipitation Climatology Centre (GPCC)–NAT (1979–2007), GPCC–HI (1979–2007) and NCC–HI (1950–2000), are conducted. In GPCC–NAT, only the natural water cycle is simulated, whereas in the other two simulations all anthropogenic water regulation schemes are activated. The GPCC–NAT and GPCC–HI simulations use GPCC precipitation data with other forcing data from ref. 24. Note that the GPCC–NAT simulation is used only for model evaluation (see Supplementary Figs S2–S4), whereas the GPCC–HI simulation is used for model evaluation, uncertainty analysis and extending the results of NCC–HI simulation until 2003. GPCC (ref. 24) and NCC (ref. 25) denote the precipitation forcing data sets used. Next, to evaluate the uncertainty in TWS simulations, three additional simulations identical to GPCC–HI based on different precipitation data sets[24]: the Global Precipitation Climatology Project version 2 (GPCP), Precipitation Reconstruction over Land (PREC/L) and Climate Prediction Center Merged Analysis of Precipitation (CMAP) are conducted.

The contributions of various TWS components to SLC are compared with the various previous estimates for the data-available period. For the period 1961–2003, which was not covered by any single simulation, we estimate various TWS contributions to SLC by adding the cumulative storage from 2001 to 2003 of the GPCC–HI simulation to the corresponding storages for the year 2000 of the NCC–HI simulation.

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References

1. Bindoff, N. *et al.* in *IPCC Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) 385–432 (Cambridge Univ. Press, 2007).
2. Church, J., White, N., Coleman, R., Lambeck, K. & Mitrovica, J. Estimates of the regional distribution of sea level rise over the 1950–2000 period. *J. Clim.* **17,** 2609–2625 (2004).
3. Lettenmaier, D. & Milly, P. Land waters and sea level. *Nature Geosci.* **2,** 452–454 (2009).
4. Chao, B. F., Wu, Y. H. & Li, Y. S. Impact of artificial reservoir water impoundment on global sea level. *Science* **320,** 212–214 (2008).
5. Huntington, T. G. Can we dismiss the effect of changes in land-based water storage on sea-level rise? *Hydrol. Process.* **22,** 717–723 (2008).
6. Milly, P., Cazenave, A. & Gennero, C. Contribution of climate-driven change in continental water storage to recent sea-level rise. *Proc. Natl Acad. Sci. USA* **100,** 13158–13161 (2003).
7. Jacob, T., Wahr, J., Tad Pfeffer, W. & Swenson, S. Recent contributions of glaciers and ice caps to sea level rise. *Nature* **482,** 514–518 (2012).
8. Gornitz, V., Rosenzweig, C. & Hillel, D. Effects of anthropogenic intervention in the land hydrologic cycle on global sea level rise. *Glob. Planet. Change* **14,** 147–161 (1997).
9. Milne, G., Gehrels, W., Hughes, C. & Tamisiea, M. Identifying the causes of sea-level change. *Nature Geosci.* **2,** 471–478 (2009).
10. Ngo-Duc, T., Laval, K., Polcher, J., Lombard, A. & Cazenave, A. Effects of land water storage on global mean sea level over the past half century. *Geophys. Res. Lett.* **32,** L09704 (2005).
11. Levitus, S., Antonov, J. & Boyer, T. Warming of the world ocean, 1955–2003. *Geophys. Res. Lett.* **32,** L02604 (2005).
12. Antonov, J., Levitus, S. & Boyer, T. Thermosteric sea level rise, 1955–2003. *Geophys. Res. Lett.* **32,** L12602 (2005).
13. Dyurgerov, M. & Meier, M. *Glaciers and the Changing Earth System: A 2004 Snapshot* (Occasional Paper 58, Institute of Arctic and Alpine Research, Univ. Colorado, 2005).
14. Lemke, P. *et al.* in *IPCC Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) 337–383 (Cambridge Univ. Press, 2007).
15. Milly, P. C. D. *et al.* in *Understanding Sea-Level Rise and Variability* (eds Church, J. A. *et al.*) Ch. 8, 226–255 (Blackwell Publishing, 2010).
16. International Commission on Large Dams, World Register of Dams, ICOLD, Paris, France (2003).
17. Pokhrel, Y. *et al.* Incorporating anthropogenic water regulation modules into a land surface model. *J. Hydrometeor.* **13,** 255–269 (2012).
18. Rodell, M., Velicogna, I. & Famiglietti, J. S. Satellite-based estimates of groundwater depletion in India. *Nature* **460,** 999–1002 (2009).
19. Wada, Y. *et al.* Global depletion of groundwater resources. *Geophys. Res. Lett.* **37,** L20402 (2010).
20. Sahagian, D., Schwartz, F. & Jacobs, D. Direct anthropogenic contributions to sea level rise in the twentieth century. *Nature* **367,** 54–57 (1994).
21. Konikow, L. F. Contribution of global groundwater depletion since 1900 to sea-level rise. *Geophys. Res. Lett.* **38,** L17401 (2011).
22. Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F. & Watkins, M. M. GRACE measurements of mass variability in the Earth system. *Science* **305,** 503–505 (2004).
23. Hanasaki, N., Kanae, S. & Oki, T. A reservoir operation scheme for global river routing models. *J. Hydrol.* **327,** 22–41 (2006).
24. Kim, H., Yeh, P. J-F., Oki, T. & Kanae, S. Role of rivers in the seasonal variations of terrestrial water storage over global basins. *Geophys. Res. Lett.* **36,** L17402 (2009).
25. Ngo-Duc, T., Polcher, J. & Laval, K. A 53-year forcing data set for land surface models. *J. Geophys. Res.* **110,** D06116 (2005).
26. Döll, P. *et al.* Impact of water withdrawals from groundwater and surface water on continental water storage variations. *J. Geodynam.* 10.1016/j.jog.2011.05.001 (2012, in the press).
27. Takata, K., Emori, S. & Watanabe, T. Development of the minimal advanced treatments of surface interaction and runoff. *Glob. Planet. Change* **38,** 209–222 (2003).
28. Oki, T. & Sud, Y. Design of Total Runoff Integrating Pathways (TRIP)—A global river channel network. *Earth Inter.* **2,** 1–37 (1998).
29. Hanasaki, N., Inuzuka, T., Kanae, S. & Oki, T. An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model. *J. Hydrol.* **384,** 232–244 (2010).
30. Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J. & Schaphoff, S. Agricultural green and blue water consumption and its influence on the global water system. *Wat. Resour. Res.* **44,** W09405 (2008).

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Author contributions

Y.N.P., T.O. and N.H. designed the research, Y.N.P. carried out all simulations, S.K., P.J-F.Y. and T.J.Y. contributed intellectually to the analysis and interpretation of results. Y.N.P. wrote the manuscript and constructed figures with contributions from all authors, all authors discussed the results.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to Y.N.P.