GROUNDWATER

The Bengal Water Machine: Quantified freshwater capture in Bangladesh

Mohammad Shamsudduha[1,2]*, Richard G. Taylor[3], Md Izazul Haq[3,4], Sara Nowreen[5], Anwar Zahid[6], Kazi Matin Uddin Ahmed[7]

Global food security depends on the sustainability of irrigated agriculture. Rising groundwater withdrawals from seasonally humid, alluvial plains across tropical Asia have enabled dry-season rice cultivation. This groundwater pumpage increases available subsurface storage that under favorable conditions amplifies groundwater replenishment during the subsequent monsoon. We empirically quantified this nature-based solution to seasonal freshwater storage capture described as the "Bengal Water Machine," revealing its potential and limitations. On the basis of a million piezometric observations from 465 monitoring wells, we show that the collective operation of ~16 million smallholder farmers in the Bengal Basin of Bangladesh from 1988 to 2018 has induced cumulative freshwater capture that volumetrically (75 to 90 cubic kilometers) is equivalent to twice the reservoir capacity of the Three Gorges Dam.

The intensification of agricultural production enabled by irrigation over the past half century has contributed unquestionably to improved global food security (*1*). Over the past half century, global groundwater withdrawals for irrigation have risen substantially to ~950 km^3/year in 2010 (*2*) owing in part to their resilience to climate variability and change (*3*).

Groundwater depletion has, however, been observed in association with intensively irrigated, large-scale farming in dryland areas such as the North China Plain, California Central Valley, and southern High Plains of the United States (*4*–*6*) and threatens global food security (*7*).

In the Indo-Gangetic Basin, groundwater depletion has recently been observed to arise from high pumping rates for irrigation but is largely restricted to semiarid regions of northern India and Pakistan (*8*).

Under Asia's Green Revolution, use of shallow groundwater by smallholder farmers continues to occur from large alluvial aquifers within seasonally humid river basins such as the Ganges-Brahmaputra, Red River, and Mekong (*9*) so that Asian farmers now account for 90% of the world's rice production (*10*). These river basins are characterized by strong seasonal imbalances in rainfall and river discharge associated with the Asian monsoon. In the Bengal Basin of Bangladesh (Fig. 1), for example, 80% of the annual discharge of the Rivers Ganges, Brahmaputra, and Meghna occurs between July and October (*11*); wet-season (May to October) and dry-season (November to April) rainfall represents 90 and 10%, respectively, of the annual total rainfall (*12*).

Conventional approaches to the storage of seasonal river discharge use dams (*13*), yet the low-lying relief of densely populated alluvial plains challenges the implementation of such infrastructure. In 1975, Revelle and Lakshminarayana (*14*) proposed an alternative solution to freshwater storage in the River Ganges Basin in which incremental increases in dry-season groundwater pumpage for irrigation near river channels lower groundwater levels and enhance leakage under gravity of river flow during the subsequent monsoon. Dubbed the "Ganges Water Machine," this intervention seeks to increase the capture and storage of seasonal freshwater surpluses while mitigating the monsoonal flood risk. We extended the concept of freshwater capture of monsoonal flows beyond perennial rivers to include a range of surface waters (such as ponds, canals, and seasonal rivers), diffuse recharge through enhanced local drainage, and irrigation return flows (supplementary text, section S3) in the Bengal Basin. We describe this broader set of recharge pathways induced by dry-season groundwater pumping as the "Bengal Water Machine" (BWM). Evidence of its operation in the Bengal Basin of Bangladesh has been noted previously where amplification of seasonal groundwater recharge occurs as a consequence of dry-season groundwater-fed irrigation for rice cultivation (*15*, *16*).

We quantified the magnitude of freshwater captured (in excess to predevelopment recharge) by the BWM from 1988 to 2018 through the collective operation of ~16 million smallholder farmers pumping shallow (well depth <100 m below ground level) groundwater for dry-season irrigation in the Bengal Basin of Bangladesh. This empirical analysis used a million weekly piezometric observations from 465 monitoring sites with time series that ranged from 24 to 54 years (median = 43 years) in duration.

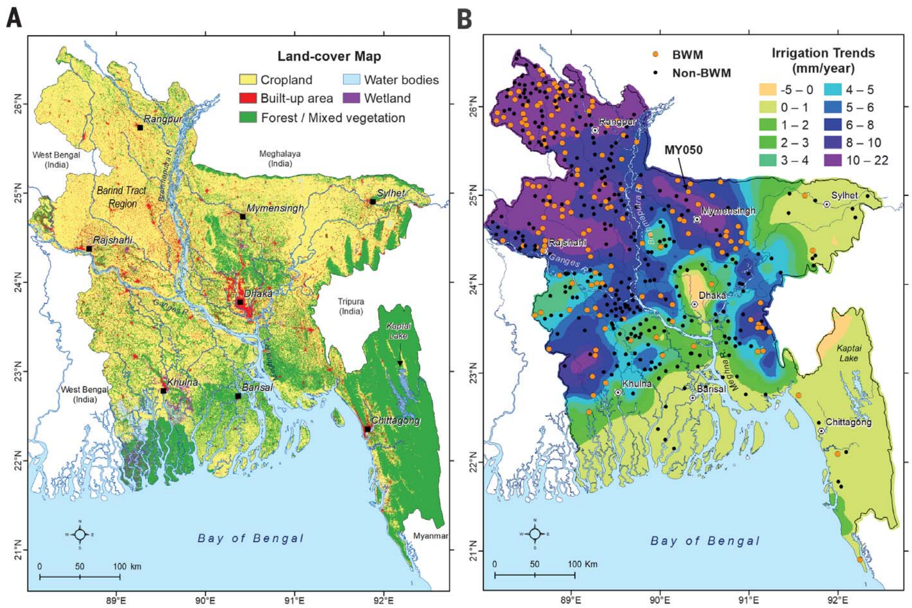

Fig. 1. Maps of land-cover and groundwater-fed irrigation trends in Bangladesh. (**A**) High-resolution (100 m) land-cover map from global land classification datasets, published by Copernicus Global Land Service (*27*). Highlighted is the Barind Tract region in the northwest of Bangladesh, where groundwater irrigation dominates. (**B**) Mapped trends (1985 to 2019) in groundwater-fed irrigation for dry-season crop cultivation in Bangladesh (supplementary text, section S1.2) and locations of 465 boreholes plotted in orange (BWM) and black (non-BWM) solid circles.

[1]Institute for Risk and Disaster Reduction, University College London, London, UK. [2]Department of Geography, University of Sussex, Brighton, UK. [3]Department of Geography, University College London, London, UK. [4]Department of Disaster Science and Climate Resilience, University of Dhaka, Dhaka, Bangladesh. [5]Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh. [6]Ground Water Hydrology Circle, Bangladesh Water Development Board, Dhaka, Bangladesh. [7]Department of Geology, University of Dhaka, Dhaka, Bangladesh.
***Corresponding author. Email: m.shamsudduha@ucl.ac.uk**

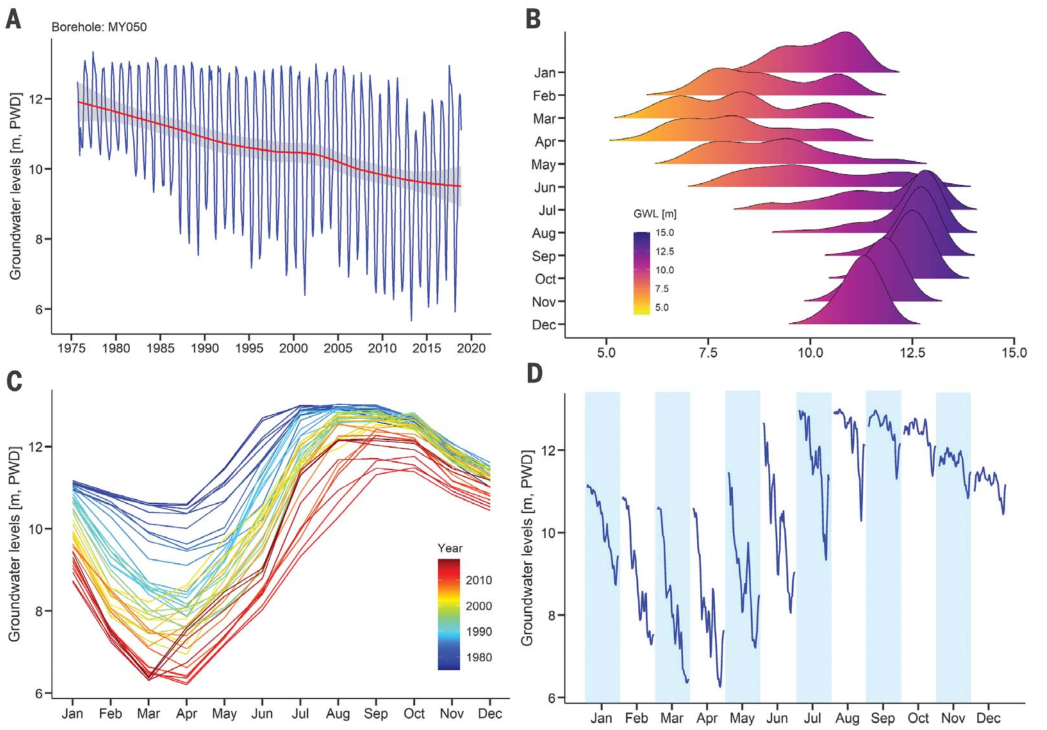

Fig. 2. Observed groundwater levels at borehole MY050 in north central Bangladesh. MY050 location is shown in Fig. 1B. (**A**) Monthly groundwater levels relative to the Public Works Datum (PWD) from September 1975 to November 2018, with a nonlinear trend line (red) as Loess smooth fit and uncertainty envelop (gray shading) around the trend line. (**B**) Probability density function showing variability in groundwater levels for each month from January to December. The *x* axis indicates groundwater levels. GWL, groundwater level. (**C**) Line plot showing monthly groundwater levels observed in each year. (**D**) Observations of groundwater levels in each month of the year from 1975 to 2018 (for example, groundwater levels in January from 1975 to 2018).

Previous estimations of freshwater capture in the River Ganges Basin have been hypothetical and based on modeled scenarios (*17*, *18*). Furthermore, our empirical analysis allowed us to report where and when the BWM has operated, which reveals both the potential and limitations of this strategy of freshwater capture.

Bangladesh occupies nearly three-quarters of the Bengal Basin (Fig. 1A) and is dominated (~50%) by cropland cover, of which 80% is irrigated with groundwater (*15*). Dry-season groundwater-fed irrigation of Boro rice (*19*) has transformed much of Bangladesh's single-crop rain-fed floodplains into highly productive double-cropping and, in places, triple-cropping lands, which makes it the world's fourth-highest producer of rice (*10*). This transformation in groundwater use accelerated in the mid-1990s after droughts in 1992 and 1994 (fig. S1). Groundwater withdrawals for irrigation are highest in the Barind area in the northwest (Fig. 1B), which is known as the "bread basket" of Bangladesh (*20*).

Quantification of freshwater capture by the BWM (additions to groundwater storage) derives from long-term, in situ observations of groundwater levels. We selected 465 multidecadal piezometric records (Fig. 1B and supplementary text, section S1) from a dense network of nearly 1250 monitoring stations (*21*) on the basis of their duration and continuity. The method for quantifying the BWM involved the following steps (supplementary text, section S2): (i) identification through cluster analysis and visual inspection of groundwater-level time series exhibiting BWM, which is characterized unambiguously by an increasing amplitude in seasonal oscillations over time (Fig. 2); (ii) calculation of annual net recharge by using the water-table fluctuation method (*15*), which is based on the annual amplitude (difference between 5th and 95th percentile values) of groundwater-level change; (iii) subtraction of mean annual recharge for the baseline (*j*th year) during the predevelopment period (R_{predev}), which is identified objectively as the period of consistent seasonal oscillations before the induction of groundwater recharge by pumping, from computed net recharge over the BWM period (R_{netBWM}); (iv) sum of annual (*i*th year) recharge induced by pumping for each groundwater-level time-series records exhibiting BWM (R_{BWM}) (Eq. 1); and (v) computation and mapping of cumulative groundwater storage captured by BWM from the product of R_{BWM} and the interpolated grid-cell area.

$$R_{\text{BWM}} = \sum\nolimits_{i=(1,2,\ldots n)}^{n} \left[R^{i}_{\text{netBWM}} - \frac{1}{m = \sum (1,2,\ldots j)} R^{j}_{\text{predev}} \right] \quad (1)$$

Figure 2 depicts the impact of the operation of the BWM in piezometric records at a site in the Old Brahmaputra floodplains of north-central Bangladesh (Fig. 1B). A rising amplitude in seasonal oscillations of groundwater levels starting in the early 1980s reflects not only the consequences of steady increases in shallow groundwater withdrawals for irrigation but also induced recharge associated with the BWM (Fig. 2A). The groundwater level at the end of the dry season in April is relatively constant (mean = 10.5 m) before the onset of groundwater-fed irrigation (1976 to 1981) but then decreases incrementally by >4 m to the period of 2013 to 2018. Variability in monthly groundwater levels is amplified most, especially toward the end of the dry season (February to May) with the continued irrigation of Boro rice (Fig. 2B). Incremental decreases in groundwater levels and their intra-annual recovery through induced recharge are amplified over the time series (Fig. 2C). Furthermore, there is evidence of a recent (after 2010) shift to an earlier start from April to March in the recharge period (Fig. 2C) that is also indicated by positive deflections over the observation period (1975 to 2018) for individual months (Fig. 2D).

Across the Bengal Basin of Bangladesh, groundwater-level dynamics reflecting the BWM are observed at 153 sites (fig. S2), which amount to approximately one-third of the 465 analyzed piezometric records (Fig. 1B). These sites are primarily located in northwestern, north- central, and southwestern Bangladesh, where increasing trends (1985 to 2019) in groundwater- fed irrigation are highest. By contrast, very few BWM sites are identified in southeastern and northeastern (such as Sylhet) regions of Bangladesh, where rising trends in irrigation are lowest in areas outside of the alluvial plain, and coastal regions, where

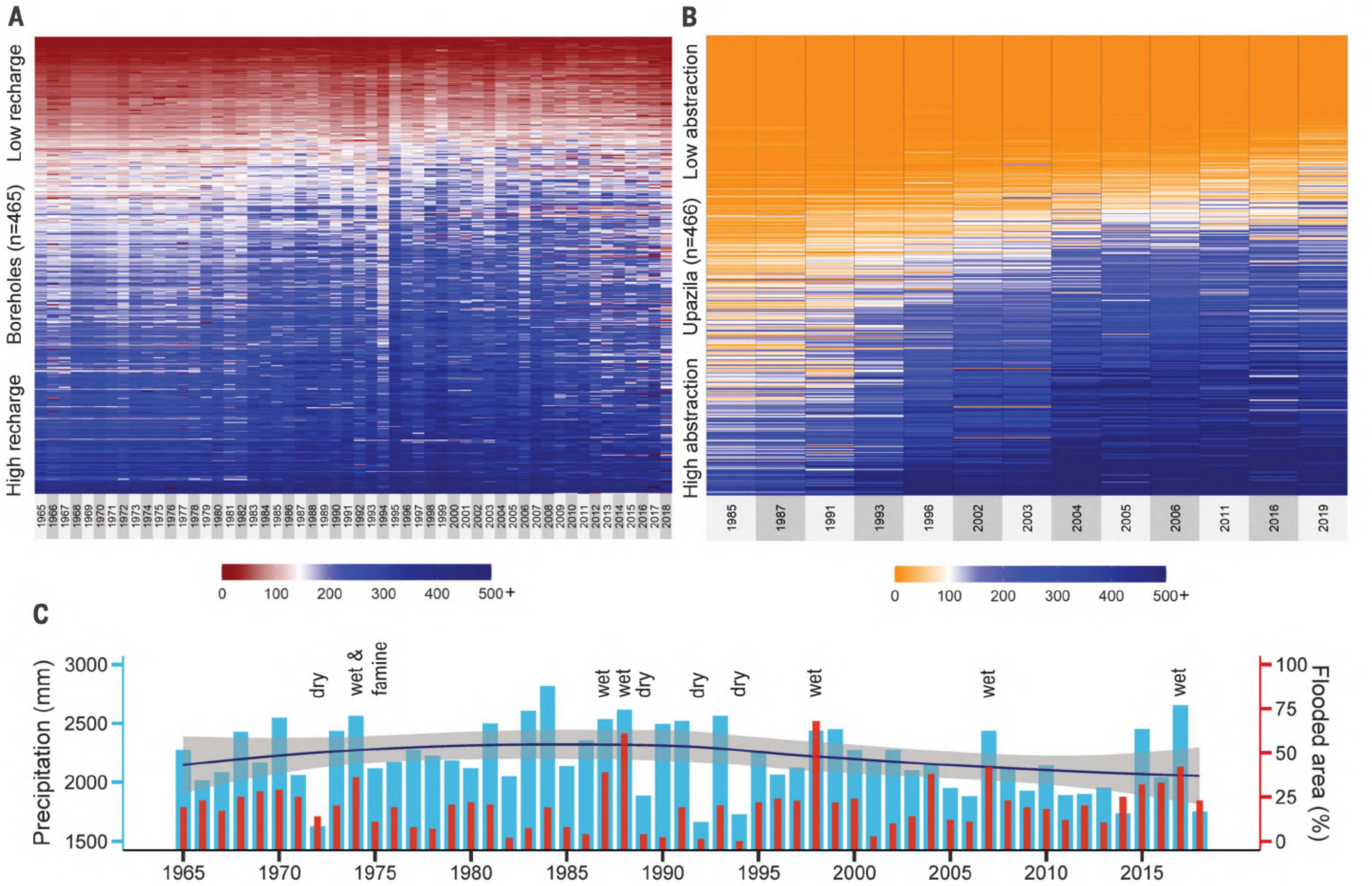

Fig. 3. Comparison of estimated groundwater recharge and abstraction for irrigation across Bangladesh. (**A**) Heatmap showing estimated recharge at 465 boreholes in Bangladesh (1965 to 2017). Missing recharge values for boreholes were infilled by using the random forest algorithm only for visualization purposes. (**B**) Heatmap showing estimated abstraction at 466 Upazilas (subdistrict) from irrigation surveys at available years between 1985 and 2019. (**C**) Bar plots of (blue) annual rainfall in Bangladesh from 1965 to 2018 (mean = 2211 mm) from Climatic Research Unit (CRU TS4.05) dataset and (red) flooded area in Bangladesh. Exceptional dry or wet conditions are noted; the blue line denotes local regression using Loess, and gray shading delimits the 95% confidence interval of fitted nonlinear trends.

the salinity of shallow groundwater restricts its use. Within areas of intensive irrigation, piezometric records that do not reflect the BWM can occur in close proximity to BWM sites. This observation points to other factors that control the operation of the BWM, including principally surface geology (fig. S3), which enables or inhibits transmission of induced recharge (supplementary text, section S3) (*15*, *22*, *23*). Furthermore, proximity to surface drainage (fig. S4) of monsoonal floodwaters (such as rivers, ponds, canals, and oxbow lakes) can enhance the magnitude of recharge through induced surface water (fig. S5) leakage (*16*, *23*).

Annual groundwater recharge computed from piezometric records at 465 sites throughout the Bengal Basin of Bangladesh shows a generalized increase from 1965 to 2017 (Fig. 3A), notably between the predevelopment (mean period 1976 to 1980) and recent (mean period 2011 to 2015) recharge (fig. S6). This rise in recharge corresponds to increasing volumes of abstracted groundwater for irrigation recorded over available years between 1985 and 2019 (Fig. 3B). Use of shallow groundwater for irrigation began in 1975 to 1976 in Bangladesh and rose steadily to a peak of nearly 1.5 million shallow wells (fig. S1) recorded between 2011 and 2015 (*24*). In the two most recent years for which records are available (2017 to 2019), a ~10% decline in shallow wells used for irrigation has been recorded and attributed to groundwater depletion (*25*) where freshwater withdrawals exceed seasonal capture through BWM. Furthermore, a reduction in the availability of piezometric time series in the database continuing to 2017 (n = 430 time series) and 2018 (n = 374) may also explain the reduction in annual recharge computed in 2018 (Fig. 3A). The influence of interannual variability in rainfall and flooded land area in the Bengal Basin (Fig. 3C) on annual groundwater recharge (Fig. 3A) is visible in both comparatively dry years (such as 1972, 1992, and 1994) and distinctly wet years (such as 1984, 1988, 1991, 1993, 1998, 1999, and 2007). The large increase in groundwater recharge, which is most pronounced in relatively dry northwestern region of Bangladesh (fig. S6) since the mid-1990s, occurred over a period when the overall trend in annual rainfall was marginally in decline.

Groundwater recharge induced by the BWM (Eq. 1, R_{netBWM}) represents contributions to freshwater capture enabled by irrigation abstraction by smallholder farmers. Geospatial maps (Fig. 4, A and B) show that freshwater capture and the likelihood of occurrence (fig. S7) through the BWM have taken place primarily in northwestern and north central areas of the Bengal Basin in Bangladesh, where increasing trends in (Fig. 1B) and magnitudes of (fig. S8) groundwater-fed irrigation are highest. Variations in computed freshwater capture presented in Fig. 4, A and B, depict uncertainty in this computation as a function of differences in applied geostatistical methods and representations of aquifer storage coefficients (supplementary text, section S2.2, and

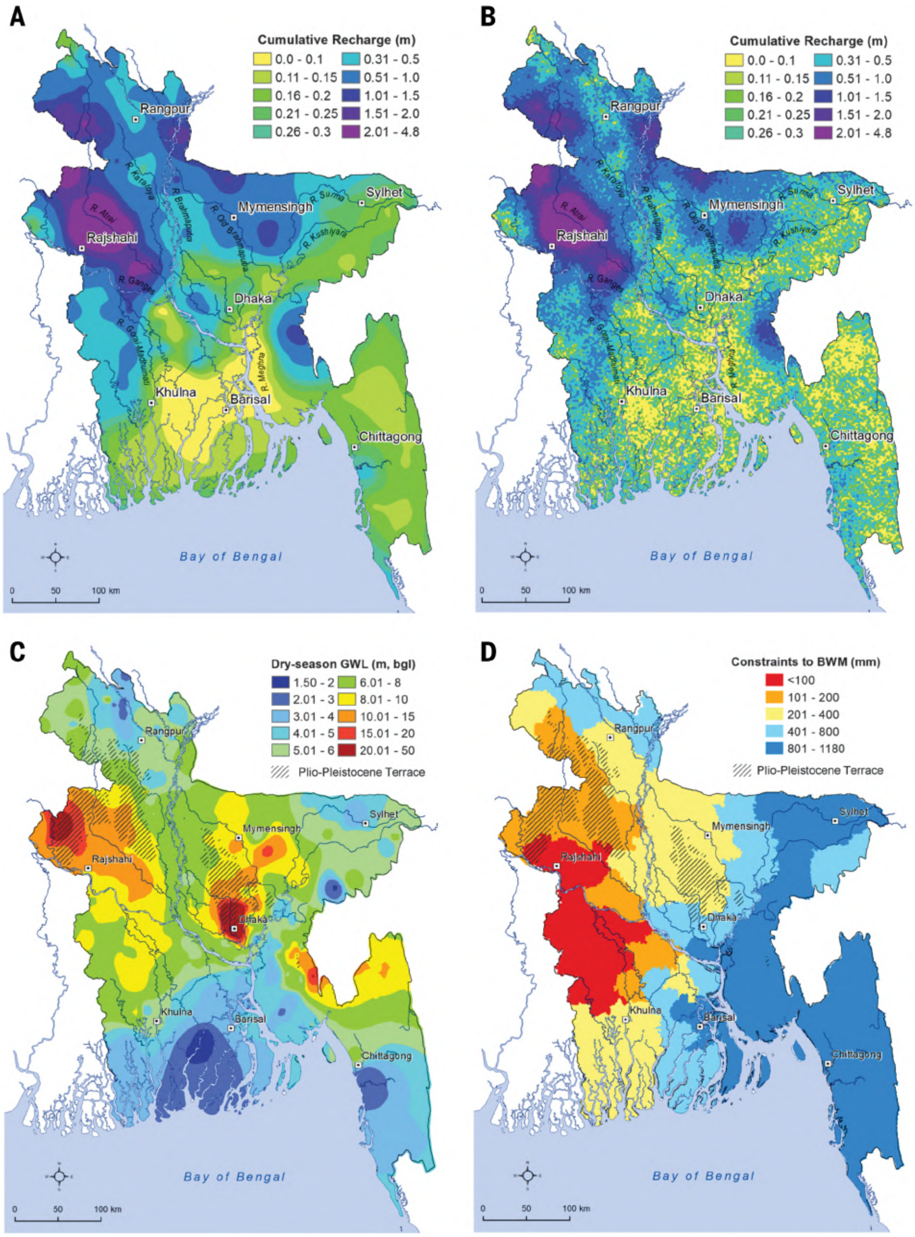

Fig. 4. Uncertainty in the estimation of freshwater capture from 1988 to 2018 through the BWM and identified constraints to BWM operation. (**A** and **B**) Cumulative induced recharge (meters) mapped at the national scale by using (A) ordinary kriging interpolation and (B) conditional sequential Gaussian simulation methods. (**C**) Depth to dry-season groundwater levels [meters below ground level (bgl)] in 2015. (**D**) Difference between potential (*23*) and long-term (1985 to 2015) mean groundwater recharge.

table S3). Notwithstanding these uncertainties, areas along the River Atrai north of Rajshahi, for example, consistently have the highest computed freshwater capture despite having the lowest mean rainfall (<1500 mm) (fig. S9) in Bangladesh. Total freshwater capture computed across the Bengal Basin of Bangladesh from 1988 to 2018 ranges from 75 to 90 km^3 of water (Fig. 4, A and B, and supplementary text, section S2.3), a volume that amounts to approximately twice the reservoir capacity of large dams such as the Three Gorges Dam (~39 km^3) in China and Hoover Dam (~37 km^3) in the United States (*26*).

Important limitations to the operation of the BWM are evident from compiled hydrographs (for example, figs. S10 to S12), which reveal locations where induced monsoonal recharge is insufficient to fully replenish groundwater abstracted during the dry season. For example, areas with a surface geology of low permeability (fig. S3) restrict the BWM and coincide with dry-season groundwater levels >8 m below ground (Fig. 4C) that render groundwater inaccessible to households reliant on shallow wells. Furthermore, the Barind region and Ganges floodplain in western Bangladesh (Fig. 4D), where observed groundwater recharge approaches or exceeds potential recharge—the latter governed by rainfall, surface geology, and flood extent (*23*)—are most at risk of realizing the limits of increased freshwater capture through the BWM. Consequently, opportunities to expand operation of the BWM in Bangladesh are now largely restricted to the River Brahmaputra floodplains (Fig. 4, C and D). Induced groundwater recharge is shown from basin-scale statistical analyses (*22*) to flush mobile arsenic from shallow groundwater.

Our analysis shows how the collective action of millions of smallholder farmers abstracting shallow groundwater to irrigate a dry-season rice crop in a tropical alluvial plain has achieved freshwater capture that rivals the world's largest dams. In doing so, we confirm the vision of this nature-based solution to seasonal freshwater capture, following a broader set of pathways than first proposed in *Science* in 1975 (*14*), while noting its limitations. Because alluvial plains in the seasonally humid tropics cover an area of nearly 4 million km^2 (fig. S13), there is scope to scale up operation of the BWM to improve the sustainability of irrigated food production globally. Evidence from the Bengal Basin, the most intensely monitored alluvial plain in the world, highlights the pivotal role played by surface geology (fig. S3) in enabling the transmission of induced recharge (*15*, *16*, *22*). Improved planning of irrigated agriculture that explicitly recognizes operation of the BWM in seasonally inundated alluvial plains can optimize freshwater capture and minimize groundwater depletion where this capture is insufficient to sustain groundwater-fed irrigation. Of strategic importance is the demonstrated resilience of this conjunctive use of groundwater and surface water to hydrological extremes that are amplified by climate change.

REFERENCES AND NOTES

1. L. Rosa, D. D. Chiarelli, M. C. Rulli, J. Dell'Angelo, P. D'Odorico, *Sci. Adv.* **6**, eaaz6031 (2020).
2. Y. Wada, D. Wisser, M. F. P. Bierkens, *Earth Syst. Dyn.* **5**, 15–40 (2014).
3. R. G. Taylor *et al*., *Nat. Clim. Chang.* **3**, 322–329 (2013).
4. M. Rodell *et al*., *Nature* **557**, 651–659 (2018).
5. B. R. Scanlon *et al*., *Proc. Natl. Acad. Sci. U.S.A.* **109**, 9320–9325 (2012).
6. W. Feng *et al*., *Water Resour. Res.* **49**, 2110–2118 (2013).
7. C. Dalin, Y. Wada, T. Kastner, M. J. Puma, *Nature* **543**, 700–704 (2017).
8. A. M. MacDonald *et al*., *Nat. Geosci.* **9**, 762–766 (2016).
9. P. Schneider, F. Asch, *J. Agron. Crop Sci.* **206**, 491–503 (2020).
10. N. Bandumula, *Proc. Natl. Acad. Sci., India, Sect. B Biol. Sci.* **88**, 1323–1328 (2017).
11. G. Rasul, *Int. J. River Basin Manage.* **13**, 387–400 (2015).
12. S. J. Ahammed, E.-S. Chung, S. Shahid, *Sustainability (Basel)* **10**, 819 (2018).
13. D. Grey, C. W. Sadoff, *Water Policy* **9**, 545–571 (2007).
14. R. Revelle, V. Lakshminarayana, *Science* **188**, 611–616 (1975).

15. M. Shamsudduha, R. G. Taylor, K. M. Ahmed, A. Zahid, *Hydrogeol. J.* **19**, 901–916 (2011).
16. S. Nowreen *et al.*, *Hydrogeol. J.* **28**, 2917–2932 (2020).
17. M. R. Khan, C. I. Voss, W. Yu, H. A. Michael, *Water Resour. Manage.* **28**, 1235–1250 (2014).
18. U. A. Amarasinghe, L. Muthuwatta, L. Surinaidu, S. Anand, S. K. Jain, *Hydrol. Earth Syst. Sci.* **20**, 1085–1101 (2016).
19. Boro is the dry-season irrigated rice crop planted from December to early February and harvested between April and June. In 2018 to 2019, Boro rice accounted for 54% of the total production of rice in Bangladesh.
20. K. Alam, *Agric. Water Manage.* **148**, 196–206 (2015).
21. M. Shamsudduha, R. E. Chandler, R. G. Taylor, K. M. Ahmed, *Hydrol. Earth Syst. Sci.* **13**, 2373–2385 (2009).
22. M. Shamsudduha, R. G. Taylor, R. E. Chandler, *Water Resour. Res.* **51**, 685–703 (2015).
23. British Geological Survey (BGS) and Bangladesh Department of Public Health Engineering (DPHE), "Arsenic contamination of groundwater in Bangladesh," D. G. Kinneburgh, P. L. Smedley, Eds. (British Geological Survey Technical Report WC/00/19, Keyworth, 2001).
24. Bangladesh Agricultural Development Corporation (BADC), "Survey report on irrigation equipment and irrigated area for the 2018-19 Boro rice season" (BADC, 2020).
25. K. M. Ahmed, in *Global Groundwater*, A. Mukherjee, B. R. Scanlon, A. Aureli, S. Langan, H. Guo, A. A. McKenzie, Eds. (Elsevier, 2021), pp. 425–438.
26. Estimated reservoir capacities derive from the UN Food and Agricultural Organization geo-referenced database on dams: https://www.fao.org/aquastat/en/databases/dams.
27. M. Buchhorn *et al.*, *Remote Sens.* **12**, 1044 (2020).

ACKNOWLEDGMENTS

We thank the Bangladesh Water Development Board (BWDB) and the Bangladesh Agricultural Development Corporation (BADC) for providing groundwater-level and irrigation datasets, respectively. We thank P. Ravenscroft and M. M. Rahman for providing a subset of irrigation data. **Funding:** R.G.T. and M.S. acknowledge support from DFID (UK government) under grant GA/11F/099/S2, "Groundwater resources in the Indo-Gangetic Basin: Resilience to climate change and pumping." S.N., M.I.H., and R.G.T. acknowledge support of a Commonwealth Split-Site Scholarship (BDCN-2014-4), Commonwealth Scholarship (BDCS-2017-60), and The Royal Society–Leverhulme Trust Senior Fellowship (ref. LT170004), respectively. **Author contributions:** M.S. and R.G.T. conceived and designed the work. M.I.H. collated the groundwater-level monitoring data; M.S. quality-controlled, processed, and analyzed groundwater-level and irrigation abstraction data and produced all the figures. R.G.T. and M.S. wrote the manuscript, with inputs from S.N., A.Z., M.I.H., and K.M.U.A.; M.S. and R.G.T. wrote the supplementary materials. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** We secured groundwater-level monitoring data from the BWDB and dry-season irrigation well information from the BADC; the latter was used to estimate groundwater abstraction. Original weekly monitored groundwater-level time-series data can be obtained from the BWDB (http://www.hydrology.bwdb.gov.bd/index.php) by making an "online data request" and payment. Processed monthly time-series data used in this paper along with codes written in R programming language can be made available upon request to the corresponding author for the purpose of reproducing or extending the analysis and creating visual illustrations. BWDB piezometric location coordinates and site-specific information as well as estimates of groundwater storage are provided in the supplementary materials. Groundwater-fed irrigation data that were estimated in this study by using dry-season well information from annual reports published by the BADC are also available in the supplementary materials.

SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.abm4730
Materials and Methods
Supplementary Text
Figs. S1 to S23
Tables S1 to S4
References (*28–60*)

Submitted 20 September 2021; accepted 20 July 2022
10.1126/science.abm4730

Science

The Bengal Water Machine: Quantified freshwater capture in Bangladesh

Mohammad ShamsudduhaRichard G. TaylorMd Izazul HaqSara NowreenAnwar ZahidKazi Matin Uddin Ahmed

Science, 377 (6612), • DOI: 10.1126/science.abm4730

Recharge!
In many dryland areas, irrigated agriculture depends on groundwater, and food cultivation can be disrupted if too much is withdrawn. Rainfall replenishes groundwater, but how much can be captured and through what mechanisms? Shamsudduha *et al*. calculated the magnitude of seasonal freshwater underground storage capture in the Bengal Basin of Bangladesh over the past 40 years (see the Perspective by Mukherji). They found that monsoon rainfall has recharged 75 to 90 cubic kilometers of water over that time, a volume equivalent to twice the reservoir capacity of the Three Gorges Dam. —HJS