The Bengal Water Machine: Quantified freshwater capture in Bangladesh

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Global food security depends upon 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. Here, we quantify empirically for the first time this nature-based solution to seasonal freshwater storage capture described as 'The Bengal Water Machine', revealing its potential and limitations. Based on a million piezometric observations from 465 monitoring wells, we show 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 (75-90 km^3) is equivalent to twice the reservoir capacity of the Three Gorges Dam.

The intensification of agricultural production enabled by irrigation over the last half century has contributed unquestionably to improved global food security (*1*). Over the last half century, global groundwater withdrawals for irrigation have risen substantially to ~950 km^3/year in 2010 (*2*) due 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 semi-arid 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, respectively, 90% and 10% of the annual total rainfall (*12*).

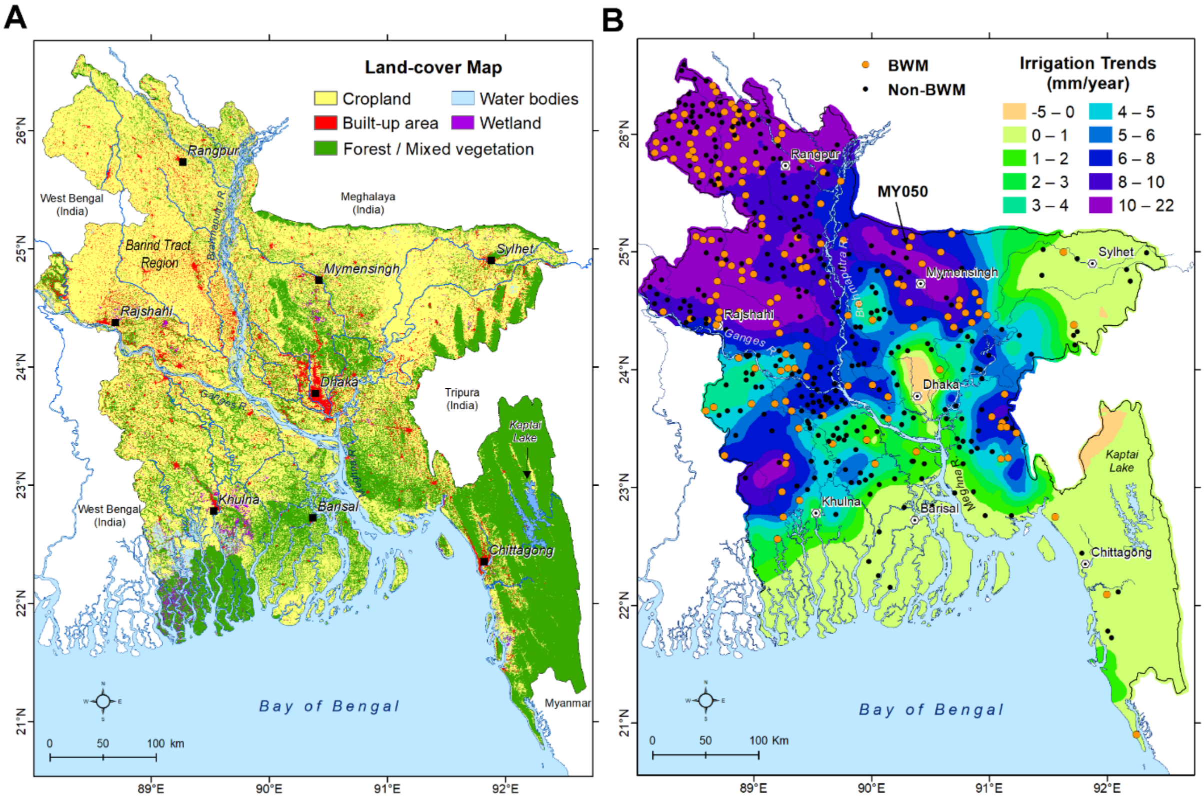

Fig. 1. Maps of land-cover and groundwater-fed irrigation trends in Bangladesh. (**A**) High-resolution (100 m) land-cover map from global land classification datasets published by Copernicus Global Land Service (*13*) highlighting the Barind Tract region in northwest of Bangladesh where groundwater irrigation dominates; (**B**) mapped trends (1985-2019) in groundwater-fed irrigation for dry-season crop cultivation in Bangladesh (see supplementary materials section S1.2), and locations of 465 boreholes plotted in red (BWM: Bengal Water Machine) and black (non-BWM) solid circles.

Conventional approaches to the storage of seasonal river discharge employ dams (*14*) yet the low-lying relief of densely populated alluvial plains challenges the implementation of such infrastructure. In 1975, Revelle and Lakshminarayana (*15*) proposed an alternative solution to freshwater storage in the River Ganges Basin whereby incremental increases in dry-season groundwater pumpage for irrigation near river channels lowers groundwater levels and enhances 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. Here, we extend the concept of freshwater capture of monsoonal flows beyond perennial rivers to include a range of surface waters (e.g., ponds, canals, seasonal rivers), diffuse recharge via enhanced local drainage, and irrigation return flows (see 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 (*16, 17*).

Here, we quantify, for the first time, the magnitude of freshwater captured (i.e., in excess to pre-development recharge) via the BWM from 1988 to 2018 through the collective operation of ~16 million smallholder farmers pumping shallow (well depth <100 m below ground level, bgl) groundwater for dry-season irrigation in the Bengal Basin of Bangladesh. This empirical analysis employs a million weekly piezometric observations from 465 monitoring sites with time series that range from 24 to 54 years (median = 43 years) in duration. Previous estimations of freshwater capture in the River Ganges Basin have been hypothetical, based on modeled scenarios (*18, 19*). Further, our empirical analysis allows us to report where and when the BWM has operated, revealing 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 (*16*). Dry-season groundwater-fed irrigation of Boro rice (*20*) has transformed much of Bangladesh's single-crop rainfed floodplains into highly productive double and, in places, triple cropping lands, making it the world's fourth highest producer of rice (*10*). This transformation in groundwater use accelerated in the mid-1990s following droughts in 1992 and 1994 (supplementary materials fig. S1). Groundwater withdrawals for irrigation are highest in the Barind area in the northwest (Fig. 1B), known as the 'bread basket' of Bangladesh (*21*).

Quantification of freshwater capture by the BWM (i.e., additions to groundwater storage) derives from long-term, *in situ* observations of groundwater levels. We selected 465 multidecadal piezometric records (Fig. 1B) (supplementary materials section S1) from a dense network of nearly 1,250 monitoring stations (*22*) based on their duration and continuity. The method for quantifying the BWM involved the following steps (section S2): (i) identification through cluster analysis and visual inspection of groundwater-level times series exhibiting BWM, which is characterized unambiguously by an increasing amplitude in seasonal oscillations over time (Fig. 2); (ii) calculation of annual net recharge using the Water-Table Fluctuation (WTF) method (*16*) based on the annual amplitude (i.e., difference between 5th and 95th percentile values) of groundwater-level change; (iii) subtraction of mean annual recharge for the baseline (j^{th} year) during pre-development period (R_{predev}), identified objectively as the period of consistent seasonal oscillations prior to 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 times 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 interpolated grid-cell area.

$$R_{BWM} = \sum_{i=(1,2,\ldots n)}^{n} \left[R_{netBWM}^{i} - \frac{1}{m=\sum(1,2,\ldots j)} \left(R_{predev}^{j} \right) \right] \qquad \text{(eq. 1)}$$

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). Here, the groundwater level at the end of the dry season in April is relatively constant (mean = 10.5 m) prior to the onset of groundwater-fed irrigation (1976-1981) but then decreases incrementally by over 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-May) with the continued irrigation of Boro rice (Fig. 2B). Incremental decreases in groundwater levels and their intra-annual recovery by induced recharge are amplified over the times series (Fig. 2C). Further, there is evidence of a recent (post-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).

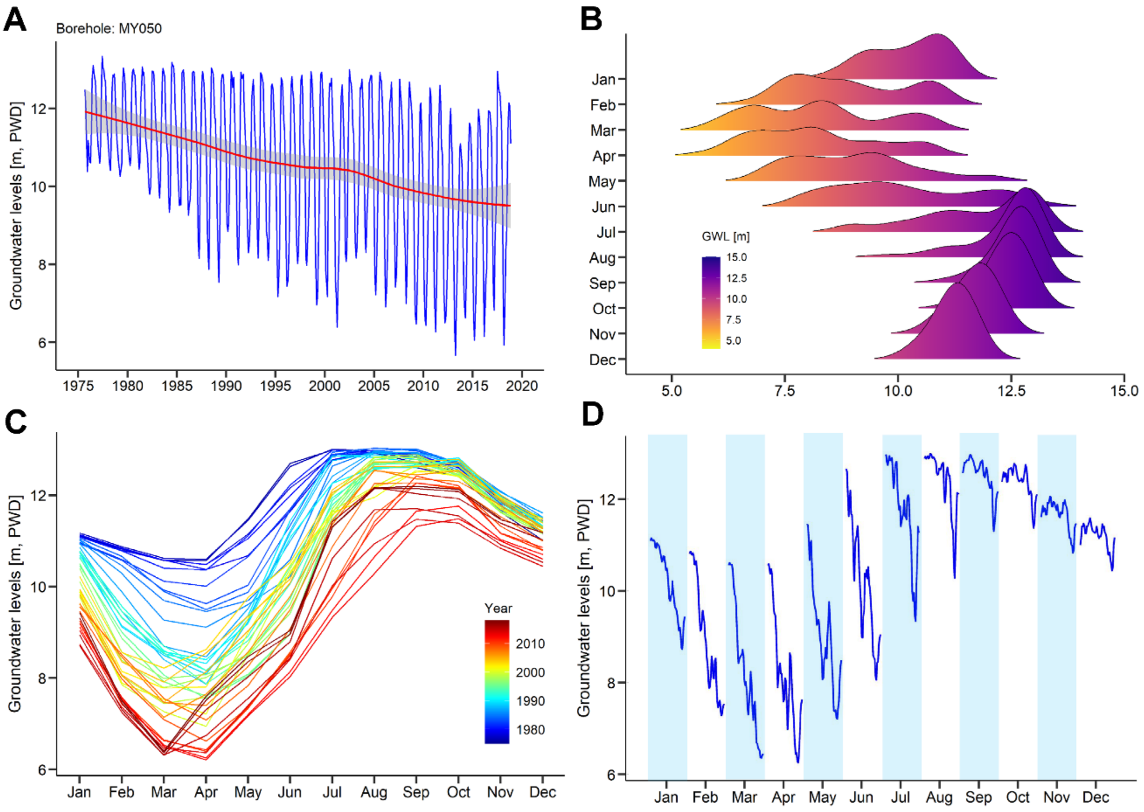

Fig. 2. Observed groundwater levels (GWLs) at borehole MY050 in north-central Bangladesh. MY050 location is shown in Fig. **1B**. (**A**) Monthly GWLs relative to the Public Works Datum (PWD) from September 1975 to November 2018 with a non-linear trend line (red) as Loess smooth fit and uncertainty envelop (grey shade) around the trend line; (**B**) probability density function showing variability in GWLs for each month from January to December, X axis denotes groundwater levels; (**C**) line plot showing monthly GWLs observed in each year; and (**D**) GWL observations in each month of the year from 1975 to 2018 (e.g., groundwater levels in January from 1975 to 2018).

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 (1985-2019) in groundwater-fed irrigation are highest. In contrast, very few BWM sites are identified in coastal, southeastern, and northeastern (e.g., Sylhet) regions of Bangladesh where rising trends in irrigation are lowest in areas outside of the alluvial plain and coastal regions where 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 (*16, 23, 24*); supplementary text section S3). Further, proximity to surface drainage (fig. S4) of monsoonal flood waters (e.g., rivers, ponds, canals, oxbow lakes) can enhance the magnitude of recharge via induced surface water (fig. S5) leakage (*17, 24*).

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 pre-development (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 1975-76 in Bangladesh and rose steadily to a peak of nearly 1.5 million shallow wells (fig. S1) recorded between 2011 and 2015 (*25*). In the two most recent years for which records are available (2017-2019), a ~10% decline in shallow wells used for irrigation has been recorded and attributed to groundwater depletion (*26*) where freshwater withdrawals exceed seasonal capture via BWM. Further, a reduction in the availability of piezometric times series in the database continuing to 2017 (n = 430) and 2018 (n = 374) may also explain the reduction in annual recharge computed in 2018 (Fig. 3A). The influence of inter-annual 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 (e.g., 1972, 1992 and 1994) and distinctly wet years (e.g., 1984, 1988, 1991, 1993, 1998, 1999, and 2007). Of note is that the large increase in groundwater recharge, most pronounced in relatively dry northwestern region of Bangladesh (fig. S6) since the mid-1990s, occurs over a period when the overall trend in annual rainfall is marginally in decline.

Groundwater recharge induced by the BWM (R_{netBWM} in eq. 1), represents contributions to freshwater capture enabled by irrigation abstraction by smallholder farmers. Geospatial maps (Fig. 4A-B) show that freshwater capture and the likelihood of occurrence (fig. S7) via the BWM has 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 figure 4A-B depict uncertainty in this computation as a function of differences in applied geostatistical methods and representations of aquifer storage coefficients (section S2.2 and supplementary 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 (Figs. 4A-B; see section S2.3 for details), 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 USA (*27*).

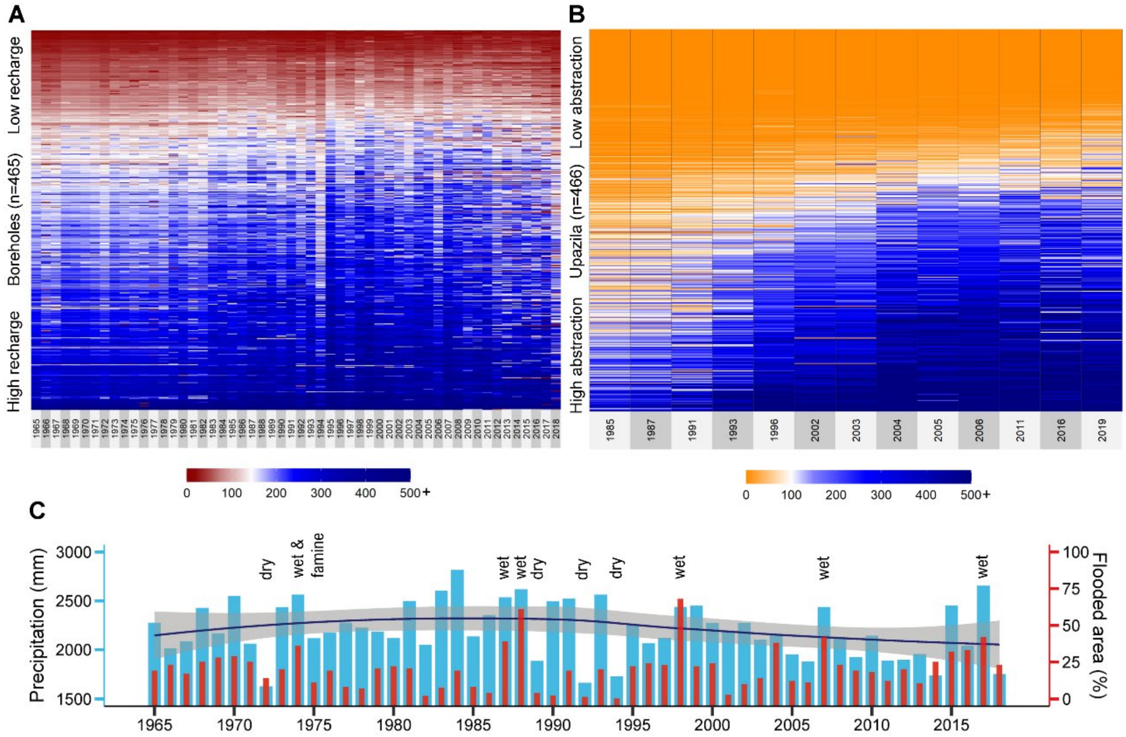

Fig. 3. Comparison of estimated groundwater recharge and abstraction for irrigation across Bangladesh. Heatmap of the panel (**A**) shows estimated recharge at 465 boreholes in Bangladesh (1965 to 2017), missing recharge values for boreholes were infilled using Random Forest algorithm only for the visualization purpose; heatmap of panel (**B**) shows estimated abstraction at 466 Upazilas (sub-district) from irrigation surveys at available years between 1985 and 2019; (**C**) barplot (blue) of annual rainfall in Bangladesh from 1965 to 2018 (mean = 2211 mm) from CRU (TS4.05) dataset, barplot (red) of flooded area in Bangladesh, exceptional dry/wet conditions are noted, blue line denotes local regression using Loess and grey shading delimits 95% confidence interval of fitted non-linear trends.

Important limitations to the operation of the BWM are evident from compiled hydrographs (e.g., figs. S10-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. Further, 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 (*24*) – 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 (Figs. 4C-D).

Induced groundwater recharge is shown from basin-scale statistical analyses (*23*) to flush mobile arsenic from shallow groundwater.

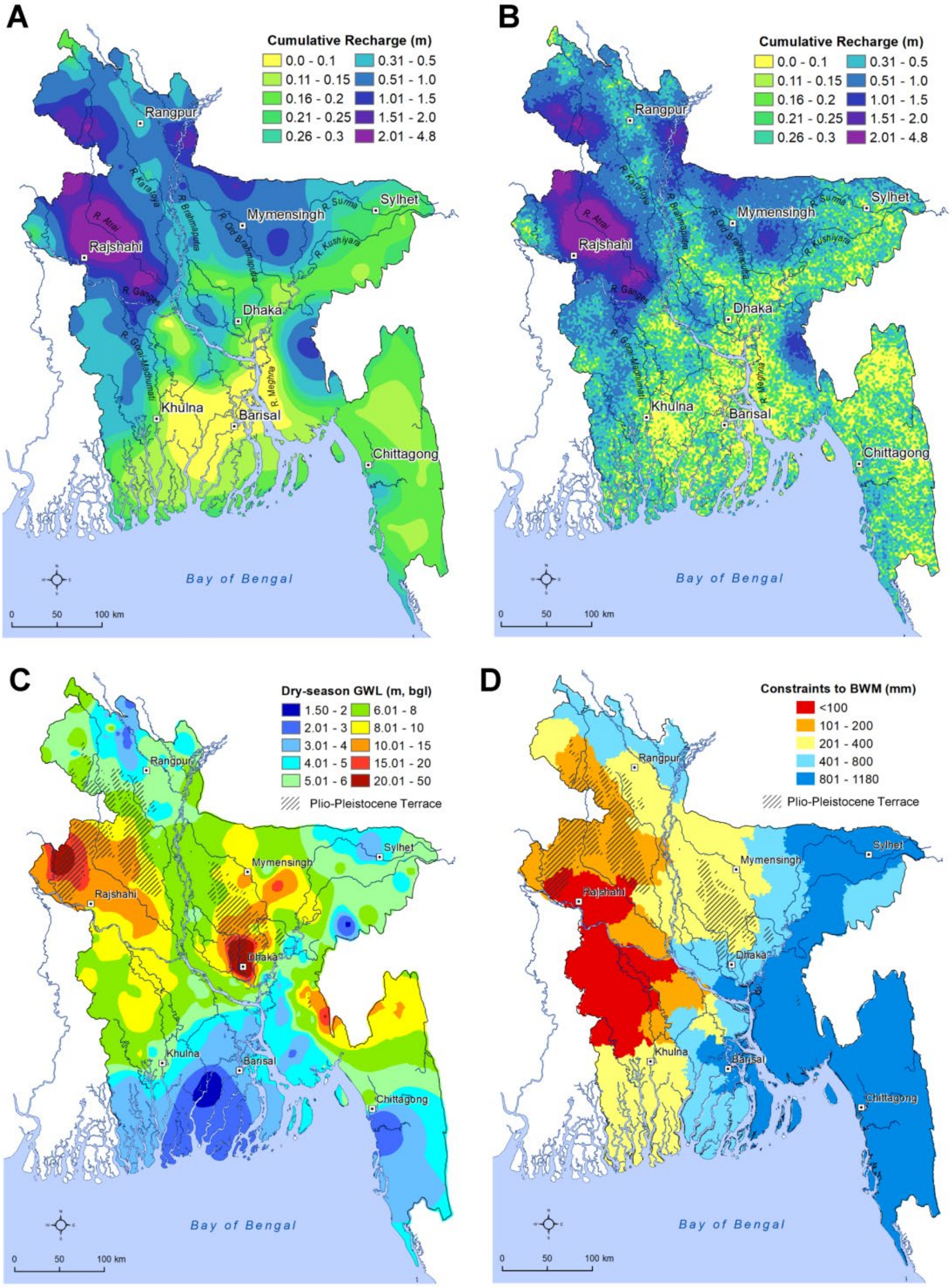

Fig. 4. Uncertainty in the estimation of freshwater capture from 1988 to 2018 via the Bengal Water Machine (BWM) (A-B) and identified constraints to BWM operation (C-D). Cumulative induced recharge (m) mapped at the national scale using ordinary kriging interpolation (**A**) and conditional sequential Gaussian simulation (**B**) methods; (**C**) depth to dry-season groundwater levels (m below ground level, bgl) in 2015; and (**D**) difference between potential (*24*) and long-term (1985–2015) mean groundwater recharge.

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 (*15*), while noting its limitations. As 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 (*16, 17, 23*). 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.

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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. gratefully 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.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 Bangladesh Water Development Board (BWDB) and dry-season irrigation well information from the Bangladesh Agricultural Development Corporation (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) through 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 using dry-season well information from annual reports published by the BADC, are also available in the supplementary materials.

Supplementary Materials

Materials and Methods
Supplementary Text
References (*28*–*64*)
Figs. S1 to S23
Tables S1 to S4