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Groundwater quality and depletion in the Indo-Gangetic Basin mapped from *in situ* observations

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Groundwater abstraction from the transboundary Indo-Gangetic Basin comprises 25% of global groundwater withdrawals, sustaining agricultural productivity in Pakistan, India, Nepal and Bangladesh. Recent interpretations of satellite gravity data indicate that current abstraction is unsustainable[1-3], yet these large-scale interpretations lack the spatio-temporal resolution required to govern groundwater effectively[4,5]. Here we report new evidence from high-resolution *in situ* records of groundwater levels, abstraction and groundwater quality, which reveal that sustainable groundwater supplies are constrained more by extensive contamination than depletion. We estimate the volume of groundwater to 200 m depth to be >20 times the combined annual flow of the Indus, Brahmaputra and Ganges, and show the water table has been stable or rising across 70% of the aquifer between 2000 and 2012. Groundwater levels are falling in the remaining 30%, amounting to a net annual depletion of 8.0 ± 3.0 km^3. Within 60% of the aquifer, access to potable groundwater is restricted by excessive salinity or arsenic. Recent groundwater depletion in northern India and Pakistan has occurred within a longer history of groundwater accumulation from extensive canal leakage. This basin-wide synthesis of *in situ* groundwater observations provides the spatial detail essential for policy development, and the historical context to help evaluate recent satellite gravity data.

The Indo-Gangetic Basin (IGB) alluvial aquifer system is one of the world's most important freshwater resources. Formed by sediments eroded from the Himalayas, and redistributed by the Indus, Ganges and Brahmaputra river systems, the IGB aquifer forms a flat fertile plain across Pakistan, northern India, southern Nepal and Bangladesh (Fig. 1). Fifteen to twenty million water wells abstract an estimated 205 km^3 yr^{-1} (circa 2010) and this volume continues to increase at 2–5 km^3 yr^{-1}, as farmers intensify agricultural production. Abstraction is unevenly distributed (Fig. 1), yet supplies drinking water for rural and urban populations across the full extent of the IGB. The aquifer system is usually represented as a single category on hydrogeological maps[6]. However, in practice the system is complex and heterogeneous, with large spatial differences in permeability, storage, recharge and water chemistry that can also vary with depth. This complexity strongly influences how each part of the aquifer responds to stresses[7]. The IGB is home to the largest surface water irrigation system in the world, constructed during the nineteenth and early twentieth century to redistribute water from the Indus and Ganges through a canal network >100,000 km long. Increasing groundwater use for irrigation poses legitimate questions about the future sustainability of abstraction from the basin, and water security of this region remains a major social–political concern[8].

Recent discussion of water security has been dominated by interpretations of remotely sensed gravity data from the GRACE mission gathered at a scale of 400 × 400 km (refs 1–3). These analyses point to a general reduction in terrestrial water storage in northern India and Pakistan since data became available in 2002, equivalent to approximately 40 mm yr^{-1} (ref. 1) with annual variability[9]. These studies are, however, poorly constrained by ground-based observations. Local field studies provide partial insight into system dynamics that include evidence of: declining groundwater levels[10–12], salinization of shallow groundwater[13,14] and increasing groundwater nitrate concentrations[15]. Further, the occurrence of geogenic arsenic in shallow groundwater has been observed across extensive areas of the aquifer in Bangladesh[16,17] and throughout other parts of the basin, primarily where Holocene alluvial deposits dominate. Additional uncertainty in future groundwater security has been introduced by forecasts

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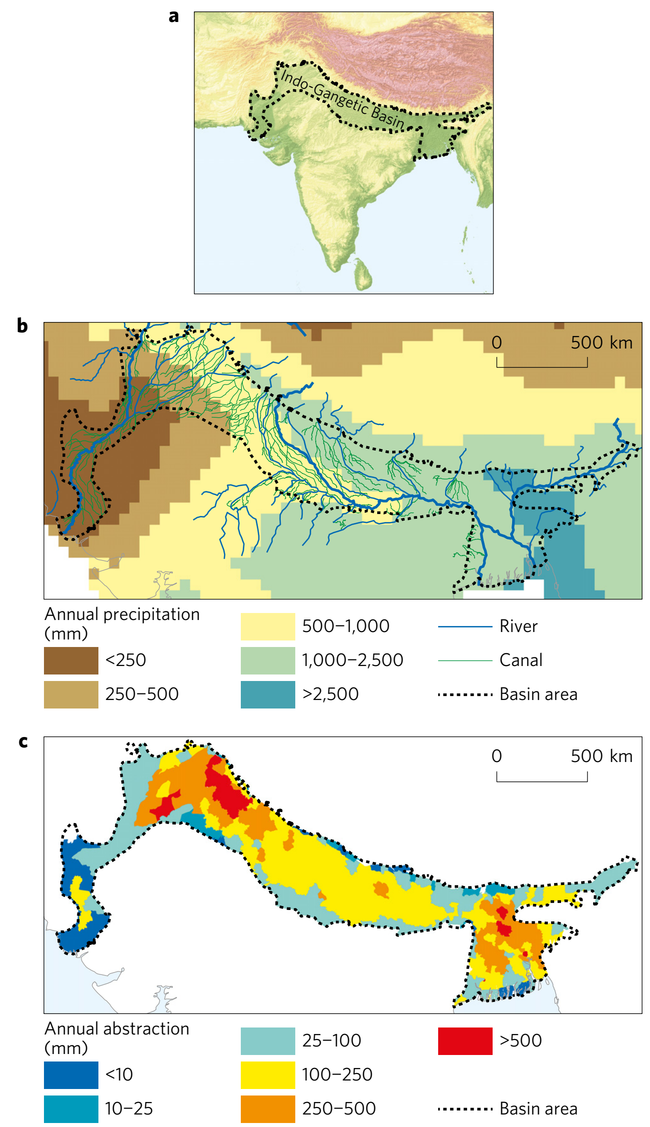

Figure 1 | The location, hydrology and abstraction from the IGB aquifer system. a, Location of the IGB. **b**, Mean annual precipitation 1950–2010[30], rivers and major canal distribution. **c**, Estimated mean annual groundwater abstraction in 2010, showing the high groundwater abstraction in northwest India, northern Pakistan and central and northern Bangladesh. Total groundwater abstraction from the aquifer is 205 km^3, approximately 25% of the global total.

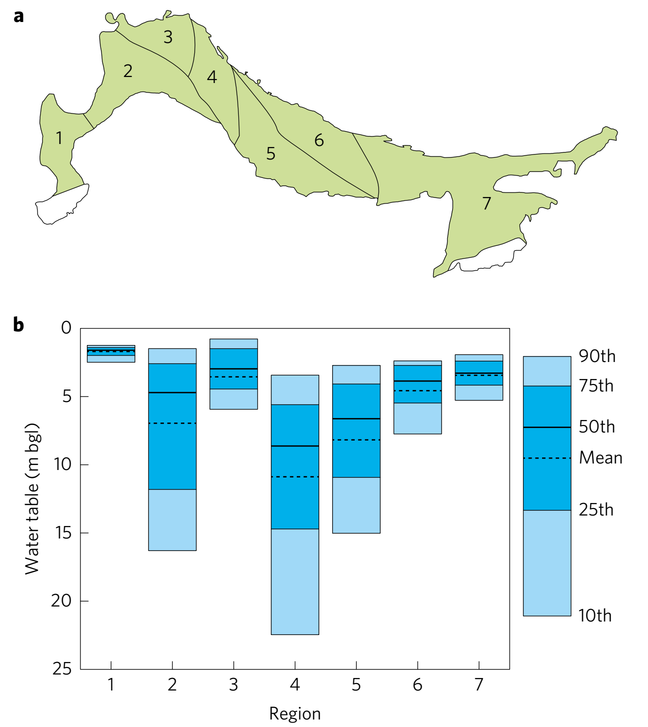

Figure 2 | Groundwater-level variations across the IGB aquifer system. a, Location of analysis regions (divided by aquifer and climate): (1) Sindh; (2) middle Indus; (3,4) upper Indus; (5) drier Uttar Pradesh; (6) wetter Uttar Pradesh; and (7) Lower Ganges and Bengal basin. **b**, Data from 3,429 monitoring points showing mean water-table depths in individual wells for the period 2000–2012; areas with high abstraction and lower rainfall show deepest groundwater levels and a wide range in measured groundwater level.

of climate change and the potential for substantial changes to precipitation, river flows and groundwater recharge[18,19].

Here we present, for the first time, an analysis of the status of groundwater across the IGB alluvial aquifer based entirely on *in situ* measurements. We use statistical analyses of multi-year groundwater-level records from 3,429 water wells and a compilation and interpretation of existing high-resolution spatial data sets and studies within Pakistan, India, Nepal and Bangladesh to assess: groundwater-level variations; groundwater quality; and groundwater storage within the top 200 m of the aquifer. In doing so, we have developed several new transboundary spatial data sets that give new insight to the aquifer system and inform improved regional modelling and water governance.

We find that the water table within the IGB alluvial aquifer is typically shallow (<5 m below ground level) and relatively stable since at least 2000 throughout much of the basin, with some important exceptions. In areas of high groundwater abstraction in northwest India and the Punjab in Pakistan (Regions 2 & 4, Fig. 2) the water table can be >20 m bgl (below ground level) and in some locations is falling at rates of $>1\,m\,yr^{-1}$ (Fig. 3). In areas of equivalent high irrigation abstraction within Bangladesh, the average water table remains shallow (<5 m bgl) due to greater direct recharge and high capacity for induced recharge. Groundwater levels are deep and falling beneath many urban areas, and particularly in large groundwater-dependent cities such as Lahore, Dhaka and Delhi[20]. Shallow and rising water tables are found in the Lower Indus, parts of the lower Bengal basin, and in places throughout the IGB aquifer, as a consequence of leakage from canals, rivers and irrigation.

Compiled water-table records indicate substantial spatial variability (Fig. 3d), particularly in areas where the water table is falling by $>0.25\,m\,yr^{-1}$. Spatial variability at such scales is unresolvable by GRACE, and depends on ground-truth observations[4], which respond to the dynamics of groundwater recharge within individual canal command areas (the area irrigated by an individual canal)[21]. The water table is often rising or stable at the head of a command area where leakage is high and groundwater abstraction is lower. Towards the end of a command area, less canal water is available for use and recharge, groundwater abstraction is greater and the water table declines. Groundwater-level data from the early twentieth century in India and Pakistan show that the recent observations of falling water table in some areas are part of a much longer history (Fig. 3b). Rising groundwater levels and waterlogging were a major concern from 1875, and a consequence of leakage from the major canal construction projects which redistributed water from rivers to land. As a result, during much of the twentieth century, parts of the IGB aquifer where canals were present (Fig. 1b) accumulated groundwater at the expense of river flow to the ocean. It is important to note that, in contrast to the

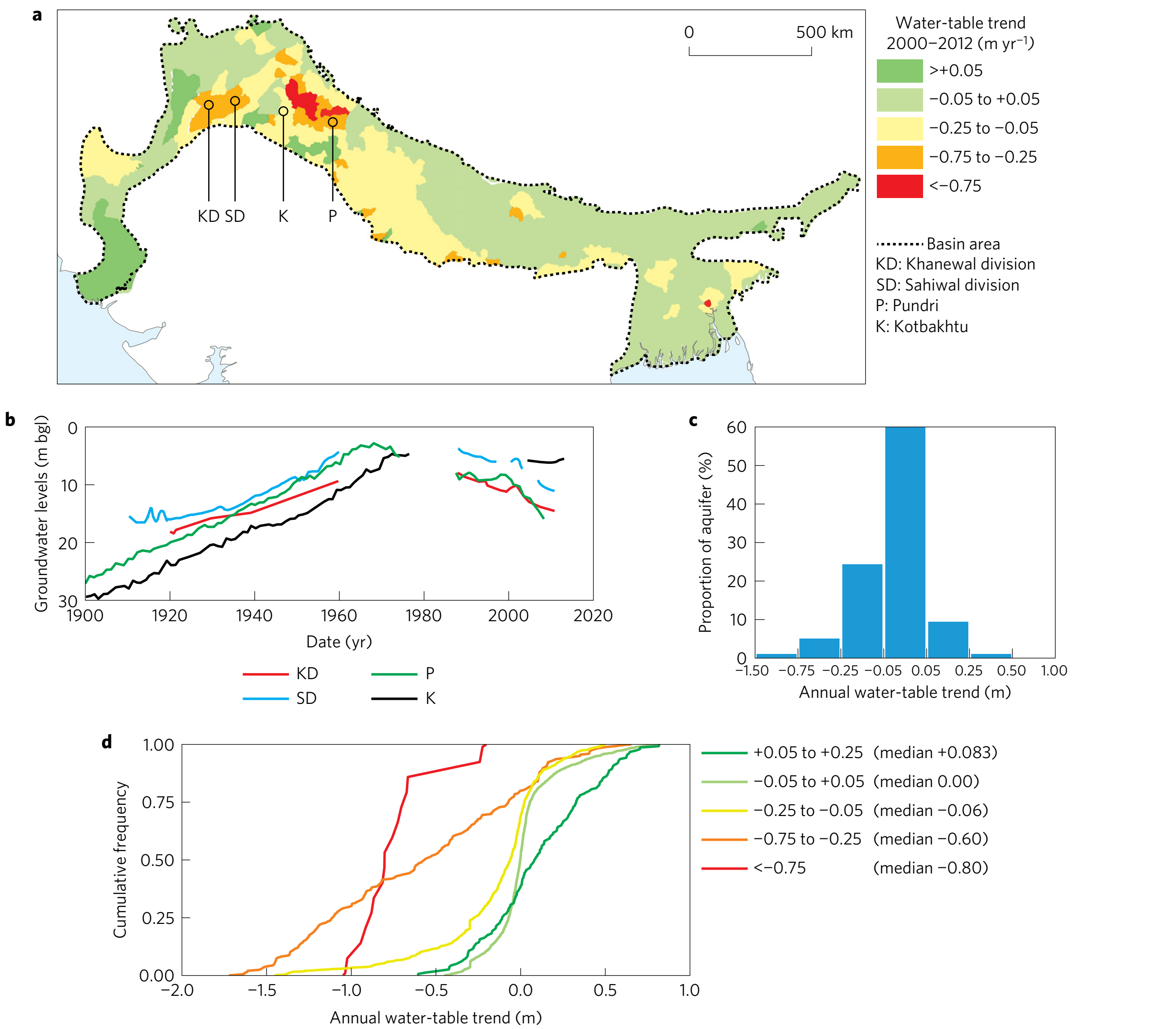

Figure 3 | Annual change in water table estimated from regional data sets and validated with 3429 multi-year records. **a**, Map of mean annual change across the basin during the period 2000–2012. **b**, Long-term groundwater-level hydrographs for four piezometers. **c**, Proportion of the aquifer with rising or falling groundwater levels, 61% of the aquifer has near stable groundwater levels. **d**, Cumulative frequency distributions for each water-table category demonstrating the low spatial variability in areas with annual changes close to zero, and the high variability where groundwater levels are falling by more than 0.25 m yr^{-1} or rising by more than 0.05 m yr^{-1}.

wealth of data available for the shallow water table, data on deep groundwater levels below 200 m are absent or sparse throughout the IGB. Also, much of the available information from the top 200 m is not depth specific, despite growing evidence that stratification within the top 200 m is important throughout the aquifer[22].

Groundwater storage and water quality within the top 200 m of the aquifer were assessed by mapping specific yield from lithological and hydrogeological data, and compiling national surveys on water quality. The total volume in the top 200 m of aquifer is 30,000 ± 14,000 km^3 (Fig. 4). This amounts to 20–30 times the combined mean annual flow in the rivers within the basin (1,000–1,500 km^3 yr^{-1}). Groundwater quality is highly variable, and often stratified with depth. The two main concerns are salinity and arsenic. Elevated arsenic is primarily a concern for drinking water, while salinity affects irrigation and also the acceptability of groundwater for drinking. Other pollutants are present and most areas are vulnerable to contamination from nitrate and faecal pathogens. Of the 30,000 km^3 of groundwater storage estimated in the basin 7,000 ± 3,000 km^3 (23%) is estimated as having salinity greater than 1,000 mg l^{-1}. A further 11,000 ± 5,000 km^3 (37%) of groundwater storage is affected by arsenic at toxic concentrations (Fig. 4).

The origin of the saline groundwater is complex, due to a variety of natural processes: saline intrusion, historic marine transgression, dissolution of evaporite layers and excessive evaporation of surface water or shallow groundwater[23]. Natural salinity is exacerbated by the long-term impact of irrigation and shallow water tables. Only the lower Bengal Basin has been subject to Quaternary marine influence[24], along with the modern day Pakistan coast. The widespread salinity in the Indus Basin and drier parts of the Upper Ganges is terrestrial in origin, and formed by a combination of natural and anthropogenic activities (Fig. 4).

Arsenic-rich groundwater occurs in chemically reducing, grey-coloured, Holocene sediments, mostly restricted to groundwater in the uppermost 100 m across the floodplains in the southern Bengal Basin, where arsenic is commonly present at >100 μg l^{-1} (refs 16,17). Less extreme arsenic concentrations, though still >10 μg l^{-1}, occur in other parts of the IGB, including: Assam, southern Nepal, the Sylhet trough in eastern Bangladesh, and within Holocene sediments along the course of the Ganges and

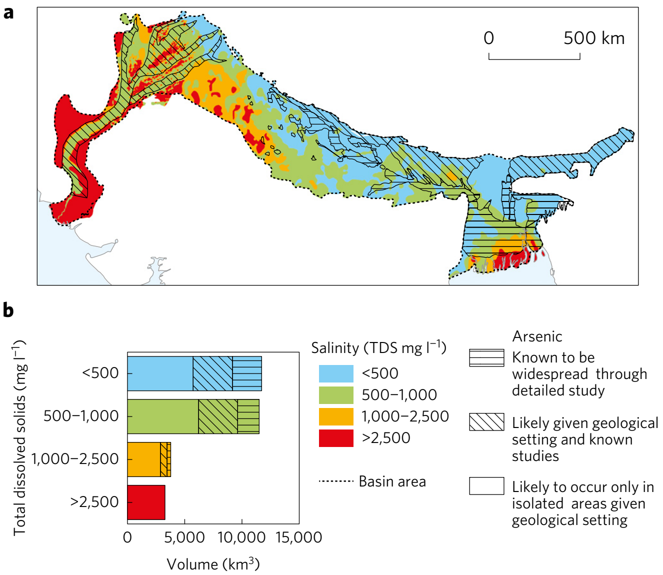

Figure 4 | Groundwater quality in the IGB aquifer system. a, Salinity measured as total dissolved solids in the groundwater and areas where arsenic is known to be widespread, or thought likely to occur. **b**, Volume of the water in the top 200 m of the aquifer by quality, total volume is 30,000 km^3 ± 14,000 km^3. Groundwater with salinity >1,000 mg l^{-1} accounts for 23% of the volume of groundwater (28% of aquifer area); and, of the remaining volume, 37% is at risk of elevated arsenic (35% by aquifer area). TDS, total dissolved solids.

Indus river systems. Abstraction can also influence arsenic flux: recent research[25] reveals that intensive abstraction of shallow groundwater can flush aqueous arsenic from the aquifer; irrigation pumping protects deeper groundwater in some instances, by creating a hydraulic barrier[26], but there is concern that high-capacity deep pumping may draw arsenic down to levels in the Bengal aquifer system which are otherwise of good quality. Despite this concern, the only re-sampling study to date[27] recorded no change in groundwater chemistry from 46 abstraction wells >150 m deep; retardation is expected to delay vertical migration by centuries[28].

Estimated trends in groundwater storage for the IGB alluvial aquifer, derived from *in situ* measurements of water-table variations (Fig. 3) and estimates of specific yield derived across the basin, indicate a net average annual groundwater depletion within the period 2000–2012 of 8.0 $km^3\ yr^{-1}$ (range 4.7–11.0 $km^3\ yr^{-1}$) with significant variation across the basin (Supplementary Fig. 2). The largest depletion occurred in areas of high abstraction and consumptive use in northern India and Pakistan: Punjab 2.6 ± 0.9 $km^3\ yr^{-1}$; Haryana 1.4 ± 0.5 $km^3\ yr^{-1}$; Uttar Pradesh 1.2 ± 0.5 $km^3\ yr^{-1}$; and Punjab Region, Pakistan, 2.1 ± 0.8 $km^3\ yr^{-1}$. In the Lower Indus, within the Sindh, groundwater is accumulating at a rate of 0.3 ± 0.15 $km^3\ yr^{-1}$, which has led to increased waterlogging of land and significant reduction in the outflow of the River Indus[12]. Across the rest of the IGB, changes in groundwater storage are generally modest (±10 mm yr^{-1}). Our estimates of annual groundwater depletion in northern India (5.2 ± 1.9 $km^3\ yr^{-1}$) are consistent with the regional estimates[1,9] when downscaled to the individual states (see Supplementary Table 2). Much of the regional depletion for Northern India observed from GRACE occurs outside the main IGB aquifer, in the desert of Rajasthan, which should be considered a separate aquifer system that is not actively recharged by rainfall, only canal leakage.

In situ observations also provide evidence of the strong link between groundwater and surface water within the basin. Given the high volume of abstraction in parts of the basin, the measured rate of water-table decline is too small to derive from direct rain-fed recharge alone (see Supplementary Fig. 3). Although this discrepancy could be attributed to errors and uncertainty in developing abstraction and water-table data sets from *in situ* data, field studies in the IGB[10,22,25] show that abstraction can markedly increase recharge, reduce natural discharge, and transport younger water deeper into the aquifer. As Fig. 3b demonstrates, leakage from canals has historically been a highly significant source of recharge, and even today local studies estimate canal leakage to be approximately 50% (ref. 29). Groundwater recharge in the IGB is not static, or a function of rainfall alone. It is highly dynamic, and influenced by abstraction, river flows and canal engineering.

The complex and dynamic nature of the IGB alluvial aquifer revealed by this study highlights the fundamental importance of regular and distributed *in situ* measurements of groundwater levels and water quality to acquire data of sufficient spatio-temporal resolution to identify processes at work in the aquifer and to inform effective governance. Specifically, the significance of groundwater contamination as the dominant regional constraint on safe water supply, and the widespread spatial variability in groundwater depletion and accumulation has not previously been established. Adverse impacts in the future can be managed through a programme of sentinel monitoring that could provide many years of advance warning of impending problems.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions

A.M.M. developed the transboundary maps and prepared the first draft of the manuscript, H.C.B. prepared the times series data set and developed maps. K.M.A., W.G.B., R.G.T. and M.S. developed data sets and interpretation for Bangladesh. L.S., M.M., A.D. and S.K.Y. developed data sets and interpretation for Nepal. F.v.S., M.B. and S.S.D.F. developed data sets and interpretation for Pakistan. K.G., M.S.R., A.M. and D.J.L. developed data sets and interpretation for India. R.C.C. and J.T. developed the first draft of the groundwater abstraction data set for comment. R.M.L. undertook statistical analysis. All edited and contributed to final manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.M.M.

Competing financial interests

The authors declare no competing financial interests.

Methods

Four separate transboundary spatial data sets were developed for the IGB across Pakistan, India, Nepal and Bangladesh using ground-based data: water-table trend per annum; groundwater abstraction; groundwater chemistry; and groundwater storage. In addition, a data set of 3,429 multi-year water-table records was developed.

Developing the multi-year water-table record (WTR) data set. More than 10,000 individual time series of groundwater-level records were collated from the IGB across India, Nepal, Bangladesh and Pakistan from numerous sources (Supplementary Table 4). A range of time periods, length and frequency of record was present within the data set, and a quality assurance process was undertaken to develop the final data set. The inclusion criteria were: a minimum length of seven years of records; at least two measurements per year at high and low water table; and records being within the time period 1975–2013. These reduced the data set to 3,810 entries. Most data (82%) are entirely within the time period 2000–2012, with 11% from 1989–2000, 6% 1993–2005 and 1% from 1975–2012. Data from outside the period 2000–2012 were used to give information in areas where no other data were available. For each individual time series the linear trend in annual mean, maximum and minimum groundwater level was calculated using a linear regression model. These values were estimated by fitting a model to the full data set with separate trend parameters (slope and intercept) for each borehole time series. The data set was first explored for skewness, and outliers were removed by applying Tukey's fences[31]. Analysis of variance (ANOVA) indicated that all effects in the model are significant (adjusted $R^2 = 0.96$), indicating the occurrence of temporal trends which differ between wells. Minimum, maximum and mean groundwater level were also calculated for each borehole for the total length of record. After the statistical treatment of the data and removal of individual outliers, the number of usable time series was reduced to 3,429, which formed the final water-table records data set (WTR). The location of the records are shown in Supplementary Fig. 1.

Summary data from the WTR data set were presented for the IGB aquifer by dividing the IGB aquifer into seven aquifer typologies. These were previously developed for the IGB to delineate areas with similar aquifer characteristics and recharge processes[32]. The seven aquifer typologies are: region 1 Sindh (moderate permeability, moderate storage; rainfall <200 mma^{-1}, recharge from canals and river); region 2 middle Indus (high permeability, high storage; rainfall 200–500 mma^{-1} recharge from canals and irrigation); Region 3 (Pakistan) and Region 4 (India) upper Indus (very high permeability, high storage; rainfall 500–1,000 mma^{-1}, recharge from rainfall and canals); region 5 drier Uttar Pradesh (very high permeability, high storage; rainfall 500–1,000 mma^{-1}, recharge from rainfall and canals); region 6 wetter Uttar Pradesh (very high permeability, high storage; rainfall 1,000–2,500 mma^{-1}, recharge from rainfall); region 7 Lower Ganges and Bengal basin (very high permeability, high storage; rainfall 1,000–2,500 mma^{-1}, recharge from rainfall and rivers).

Additional longer-term data sets were sought for the basin to help contextualize the WTR. Several historical long-term records were collated from Pakistan and India (Supplementary Table 4). Data were digitized from reports published in the 1970s and 1980s, then matched to modern data monitoring boreholes. Records are presented where there is a high degree of confidence that the modern records are from the same borehole as the older record. The records are not complete, however, and data for parts of the 1970s and 1980s are missing.

Map of annual groundwater-level trend. To develop the map of mean annual trend in water table per district area for the period 2000–2012, the WTR was combined with existing national maps and databases of groundwater-level variations (Supplementary Table 5). District area maps for Pakistan, India, Nepal and Bangladesh, as provided by Global Administration Boundaries (www.gadm.org) were used as the base. Average water-table deflection was estimated for each district area from existing published or national sources of groundwater-level variation for Pakistan and India. For Pakistan, annual district water-level trend was estimated from a survey of water-table depth mapped across the Indus Basin Irrigation System in June 2002 and repeated in June 2012[12] in conjunction with a statistical analysis of 3,175 water-level records in Punjab from 2003–2011[33]. In India, annual district water-level trend was mapped by subtracting maps of groundwater level measured in 2011 from the decadal mean 2001–2010 using the Central Groundwater Board (CGWB) published maps[34]. The district groundwater level estimated from these available data In India and Pakistan were then checked against data in the WTR data set. The Indian maps agreed well with the WTR data where groundwater levels were declining or rising markedly; however, in the published broad categories 0 to +0.25 m and 0 to −0.25 m per year, the WTR data showed that long-term trends within these ranges were generally close to zero. In these areas, the WTR was used to estimate water-level variation per district and assign new, refined categories. For districts where few WTR data were available, the average WTR annual trend calculated for the spatial extent of the existing broad category in that region was assigned to the district. For Bangladesh, a published analysis of water-table variation for the years 2003–2007 compiled from 1,267 monitoring wells from the Bangladesh Water Development Board[35,36] was adapted to map mean annual groundwater-level trend at district level. The original Bangladesh Water Development Board data set was used to calculated trend data for each district, which was checked for consistency with the published data and the 50 good-quality WTR records available for Bangladesh. For Nepal, a recently completed study of tube wells in the Terai[37] was used for information about the tube wells, and the WTR available for the districts used to assign regional water-table trends. This new combined map has systematic data bins developed across the four countries: annual fall (m) >0.75, 0.25–0.75, 0.05–0.25, stable −0.05–+0.05; and annual rise (m) 0.05–025. The WTR data for each data bin were then plotted on a cumulative frequency curve to indicate the spread of data within each bin, and the median used in further calculations of basin-wide groundwater storage changes. A further breakdown of the WTR data per region is shown in Supplementary Fig. 5.

Groundwater abstraction. A basin-wide map of current estimated groundwater abstraction was developed by combining the complete available district data for India for the year 2010 with a combination of local and published data sets for Pakistan, Nepal and Bangladesh which covered the period 2008 to 2013 (Supplementary Table 1). District maps for the four countries were used as a base, and the abstraction data from the various sources summarized or integrated to give an estimate of the annual abstraction for each district around the year 2010. For India, groundwater abstraction data for 2010/11 are collated in the Groundwater Information Booklets for individual Districts, published by the CGWB[38]. The data were extracted and plotted for each Indian district. In Pakistan, the spatial work of Cheema[39] mapping groundwater for irrigation in 2007 was integrated for each district and compared to more recent national abstraction and irrigation data presented by the Food and Agriculture Organization of the United Nations[40]. Urban groundwater abstraction was estimated from various published sources[41]. For Bangladesh, district groundwater abstraction was derived from two recent groundwater models developed for Bangladesh using available data[25,42] and supplemented with specific information on groundwater abstraction for Dhaka[43]. For the Nepal Terai, abstraction data do not exist, and volumes were estimated from a published global irrigation assessment[44]. Abstraction assigned to each district within the IGB aquifer was converted to a spatially averaged depth of water in millimetres.

Groundwater chemistry. Mapping groundwater chemistry for the IGB alluvial aquifer system focused on the distribution of salinity and arsenic, the two most significant water quality issues within the basin. There is limited information on the depth variations of groundwater quality across much of the IGB (with the exception of the lower Bengal Basin). Most studies take chemistry samples from existing pumping boreholes of unknown depth. Existing boreholes are generally less than 100 m deep, and would only very rarely exceed 200 m. Spatial information on water quality variations was assigned to the full depth of the upper 200 m of the aquifer, apart from the piedmont area, where the aquifer is physically limited to 100 m. For salinity, this may underestimate the area affected, as salinity generally increases with depth; for arsenic, this may slightly overestimate the volume affected, as there is evidence in some parts of the basin that arsenic can reduce with depth. Groundwater salinity was mapped by compiling existing information of groundwater chemistry and specific electrical conductance from national and regional surveys across the four countries (Supplementary Table 6). Salinity was represented as total dissolved solids expressed in mg l^{-1} and divided into four categories <500, 500–1,000, 1,000–2,500, and >2,500 mg l^{-1}, reflecting potential water use. The World Health Organization has no official guidelines for total dissolved solids, but suggest that <1,000 mg l^{-1} is generally acceptable for drinking water. Areas of elevated arsenic concentrations (>10 μg l^{-1}) in shallow groundwater (<200 m bgl) were determined by using a combination of available maps and national data sets, local data sets and published studies, coupled with an understanding of the distribution of Holocene deposits in the basin (Supplementary Table 7). The presence of Holocene deposits and organic-rich surface sediments is known to be a key indicator for arsenic risk[45,46]. The presence of Holocene deposits could be reliably mapped across the IGB, though organic-rich soils can be more locally variable. Therefore, the IGB was, divided into three categories: elevated arsenic known to be widespread through detailed study; elevated arsenic believed likely to occur given the geological setting and isolated studies; and elevated arsenic likely to occur only in isolated areas given the geological setting and likely conditions.

Groundwater storage. Groundwater storage in the top 200 m was calculated using an estimate of the effective thickness and specific yield (drainable porosity) of the aquifer. We estimated these properties using hydrogeological typologies[32] developed from an interpretation of the sedimentology of the basin. The interpretation incorporated a review of geological and sedimentological literature, parameterized with information on grain size and modes of deposition. For much of the IGB, the thickness is fully 200 m, reduced to 100 m in the piedmont area. Deeper confined regions of the aquifer (200–350 m) in the southern Bengal Basin were not included in this assessment. Specific yield was mapped across the basin using the available particle size distribution for the top 200 m of alluvium, and validated with several key hydrogeological studies of specific yield undertaken in different parts of the basin[32]. For each typology, the likely range in specific yield was established (Supplementary Fig. 4). Groundwater storage was then calculated using this range of estimates and the effective thickness of aquifer. Annual trends in groundwater storage were calculated using the estimates of specific yield for the IGB and the annual trend in groundwater level for the period 2000–2012 (Supplementary Table 1). The range presented represents uncertainty in specific yield, which dominates the potential uncertainty. For brevity within the main document, the range was summarized as a confidence interval.

Data availability. The maps developed for abstraction, groundwater-level trend, salinity and arsenic and groundwater storage are available from the corresponding author as gridded data on request. The sources of the underlying data including the water-table records used to develop these maps are given in the Supplementary Methods.

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