Complex patterns of groundwater depletion and quality in the Indo-Gangetic Basin from *in situ* observations

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Groundwater abstraction from the transboundary Indo-Gangetic alluvial aquifer 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, [1,2,3] 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 secure 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 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. Over 60% of the aquifer, access to potable groundwater is restricted by excessive salinity or arsenic. Recent depletion in northern India and Pakistan has occurred within a longer history of groundwater accumulation through canal leakage. This basin-wide synthesis of in-situ groundwater observations provides the spatial detail essential for policy development and the multi-decadal context for short term evaluations based on 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 (Figure 1). Fifteen to twenty million water-wells abstract an estimated 205 km^3/a (ca. 2010) and this volume continues to increase at 2–5 km^3/a, as farmers intensify agricultural production. Abstraction is unevenly distributed (Figure 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 19th and early 20th 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 400x400 km [1,2,3]. 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/a [1] with annual variability [10]. 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 [11,12,13], salinization of shallow groundwater [14,15] and increasing groundwater nitrate concentrations [16]. Further, the occurrence of geogenic arsenic in shallow groundwater has been observed across extensive areas of the aquifer in Bangladesh [17,18] and throughout other parts of the basin primarily where Holocene deposits dominate. Additional uncertainty in future groundwater security has been introduced by forecasts of climate change and the potential for substantial changes to precipitation, river flows and groundwater recharge [19,20].

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 a statistical analysis of multiyear groundwater-level records from 3429 water-wells and a compilation and interpretation of existing high resolution spatial datasets and studies within Pakistan, India, Nepal and Bangladesh to assess: (1) groundwater-level variations; (2) groundwater quality; and (3) groundwater storage within the top 200 m of the aquifer. In doing so, we have developed several new transboundary spatial datasets 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 surface) 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, Figure 2) the water-table can be >20 m bgl and in some locations is falling at rates of > 1 m/a (Figure 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 dependant cities such as Lahore, Dhaka and Delhi [21]. 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 (Figure 3d), particularly in areas where the water-table is falling by >0.25 m/a. 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) [22]. 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 20th century in India and Pakistan, show that the recent observations of falling water-table in some areas are part of a much longer history (Figure 3b). Rising groundwater levels and water-logging 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 20th century parts of the IGB aquifer where canals were present (Figure 1b) accumulated groundwater at the expense of river flow to the ocean. It is important to note that in contrast to the wealth of data available for the shallow water-table, data on deep groundwater-levels below 200 m is 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 [23].

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 (Figure 4). This amounts to 20–30 times the combined mean annual flow in the rivers within the basin (1,000 – 1,500 km^3/a). 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 1000 mg/L. A further 11,000 ± 5,000 km^3 (37%) of groundwater storage is affected by arsenic at toxic concentrations (Figure 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 [24]. Natural salinity is exacerbated by the longterm impact of irrigation and shallow water-tables. Only the lower Bengal basin has been subject to Quaternary marine influence [25] 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 (Figure 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 [17,18]. Less extreme arsenic concentrations, though still >10 μg/L, 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 Indus river systems. Abstraction can also influence arsenic flux: recent research [26] reveals that intensive abstraction of shallow groundwater can flush aqueous As from the aquifer; irrigation pumping protects deeper groundwater in some instances, by creating a hydraulic barrier [27], but there is concern that high-capacity deep pumping may draw As down to levels in the Bengal aquifer system which are otherwise of good quality [28]. Despite this concern, the only re-sampling study to date [29] 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 (Figure 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/a (range 4.7-11.0 km^3/a) with significant variation across the basin (Supplementary Figure 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/a; Haryana 1.4 ±0.5 km^3/a; and Uttar Pradesh 1.2 ±0.5 km^3/a; and Punjab Region, Pakistan, 2.1 ±0.8 km^3/a. In the Lower Indus, within the Sindh, groundwater is accumulating at a rate of 0.3 ±0.15 km^3/a, which has led to increased waterlogging of land and significant reduction in the outflow of the River Indus [13]. Across the rest of the IGB, changes in groundwater storage are generally modest (±1 cm/a). Our estimates of annual groundwater depletion in northern India (5.2 ± 1.9 km^3/a) are consistent with the regional estimates [1,10] 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 Figure 3]. Although this discrepancy could be attributed to errors and uncertainty in developing abstraction and water-table datasets from *in situ* data, field studies in the IGB [11,23,26] show that abstraction can markedly increase recharge, reduce natural discharge, and induce younger water deeper into the aquifer. As Figure 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% [30]. 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.

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Author Contributions

AM developed the transboundary maps and prepared the first draft of the manuscript, HB prepared the times series dataset and developed maps, KA, WB, RT and MS, developed datasets and interpretation for Bangladesh, LS, MM, AD and SY developed datasets and interpretation for Nepal, FS, MB and SF developed datasets and interpretation for Pakistan and KG, MR, AMuk and DL developed datasets and interpretation for India. RC and JC developed the first draft of the groundwater abstraction dataset for comment. ML undertook statistical analysis. All edited and contributed to final manuscript.

Competing Financial Interests statement

There are no competing financial interests.

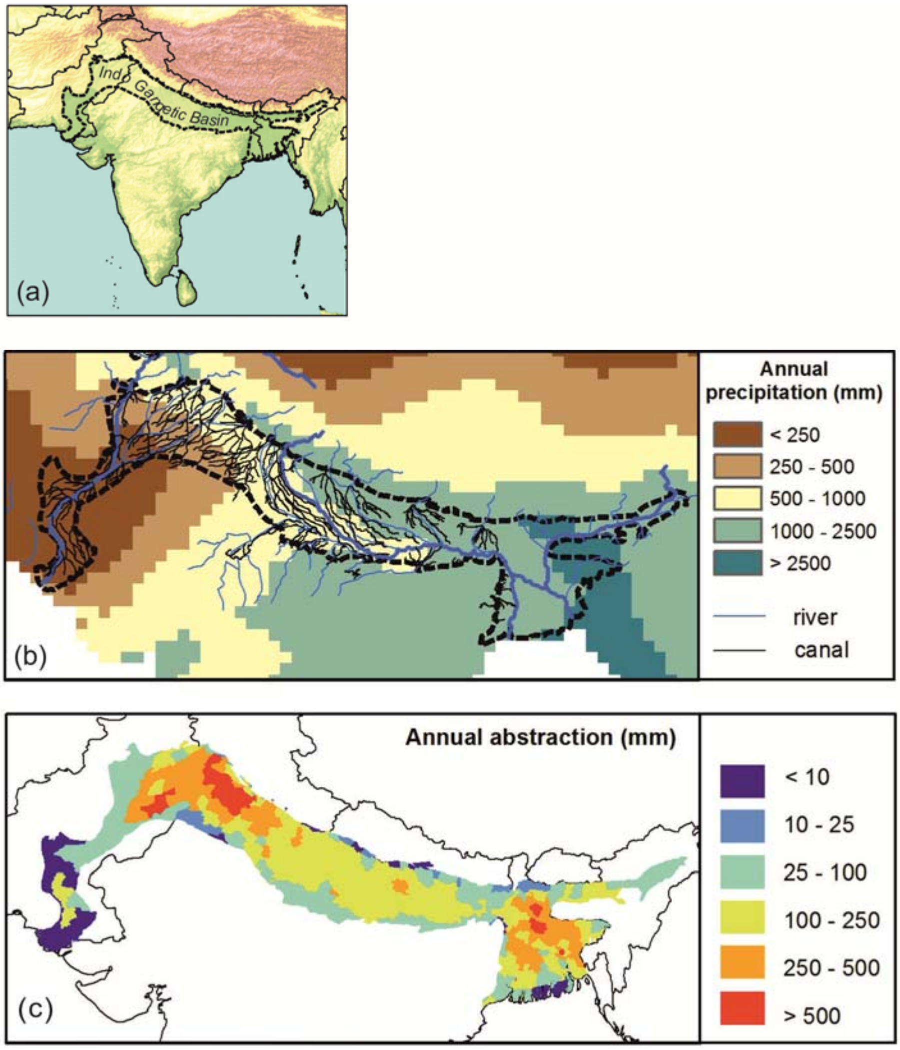

Figure 1 The location, hydrology and abstraction from the Indo Gangetic Basin alluvial aquifer system (IGB): (a) location of the IGB; (b) mean annual precipitation 1950 – 2010 [9], rivers and major canal distribution; and (c) estimated mean annual groundwater abstraction in 2010, showing the high groundwater abstraction in north west India, northern Pakistan and Central and Northern Bangladesh. Total groundwater abstraction from the aquifer is 205 km^3, approximately 25% of the global total.

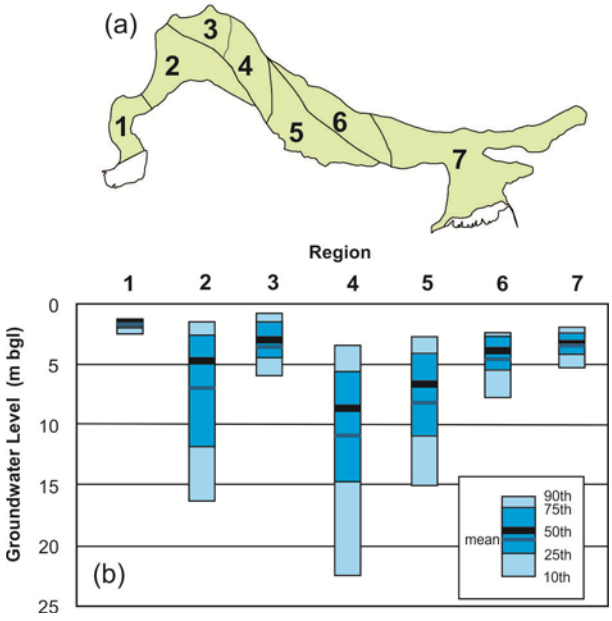

Figure 2. Water-table variations across the IGB aquifer system: (a) location of analysis regions (divided by aquifer and climate) and long-term monitoring sites, 1 Sindh; 2 middle Indus;,3,4 upper Indus; 5 drier Uttar Pradesh; 6 wetter Uttar Pradesh; 7 Lower Ganges and Bengal basin; (b) data from 3429 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.

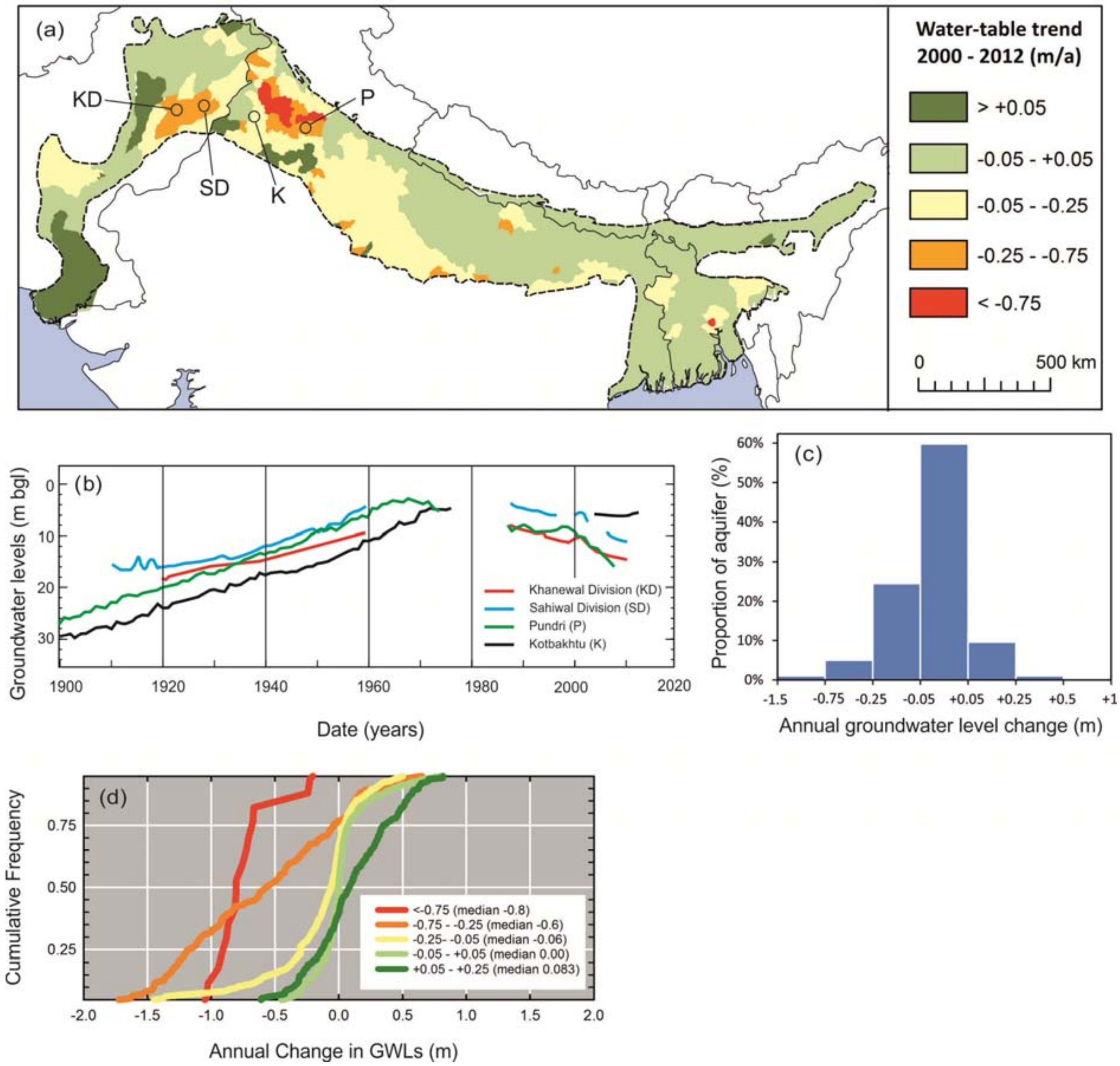

Figure 3. Annual change in water-table estimated from regional datasets and validated with 3429 multi-year records: (a) map of mean annual change across the basin during the period 2000-2012; (b) longterm groundwater-level hydrographs for four piezometers; (c) proportion of the aquifer with rising or 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 water levels are falling by more than 0.25 m per year or rising by more than 0.05 m per year

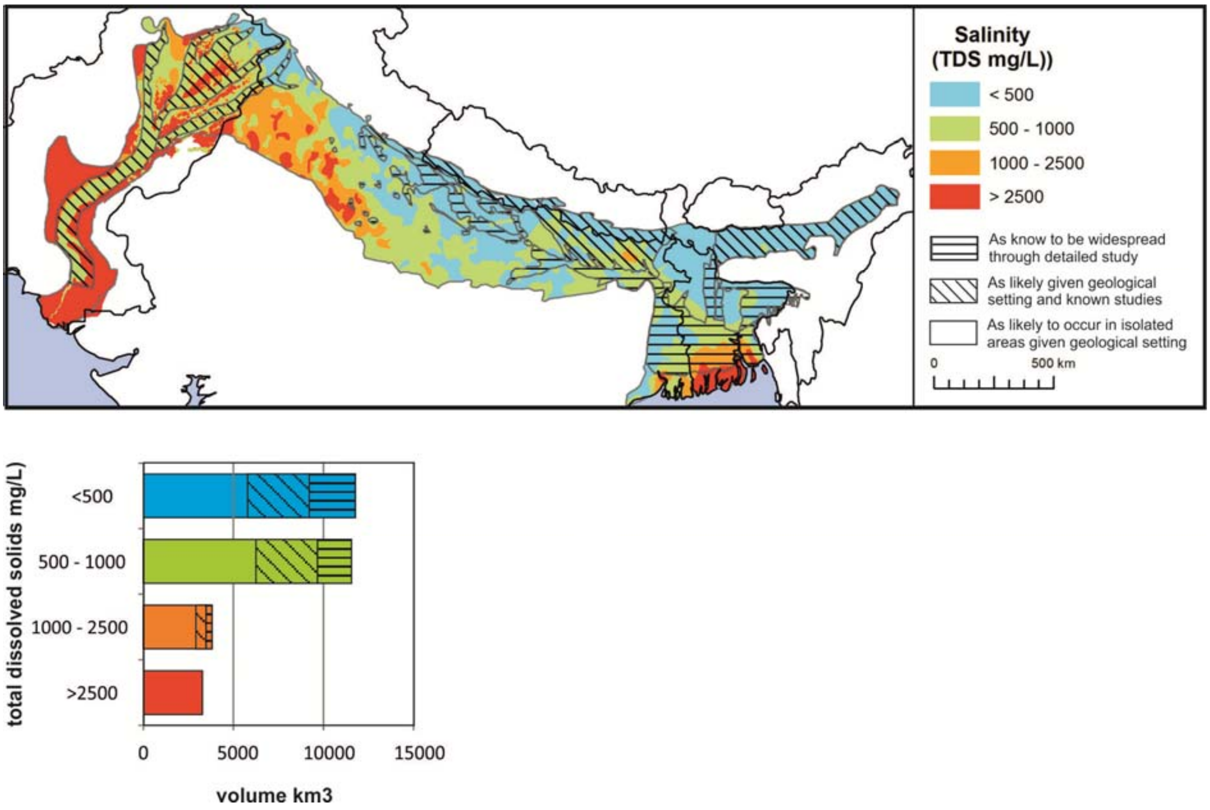

Figure 4. Groundwater quality in the IGB aquifer system: (a) salinity measured as total dissolved solids in the groundwater and areas where arsenic is known to be widespread, or thought likely to occur; and (b) the volume of the water in the top 200 m of the aquifer by quality, total volume is 30,000 km^3 ±14,000 km^3. Groundwater with salinity>1000 mg/L accounts for 23% of the volume of groundwater; and of the remaining volume 37% is at risk of elevated arsenic (28% and 35% respectively by aquifer area).

Methods

Four separate transboundary spatial datasets 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 dataset of 3429 multi-year water-table records was developed.

Developing the multiyear water-table record (WTR) dataset

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 dataset and a quality assurance process was undertaken to develop the final dataset. The inclusion criteria were: a minimum length of 7 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 dataset to 3810 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 outwith 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 dataset was first explored for skewness and outliers were removed by applying Tukey's fences [31]). 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 3429, which formed the final water-table records dataset (WTR). The location of the records are shown in Supplementary Figure 1.

Summary data from the WTR dataset 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 1 *Sindh* (moderate permeability, moderate storage; rainfall <200 mma^{-1}, recharge from canals and river); 2 *middle Indus* (high permeability, high storage; rainfall 200 – 500 mma^{-1} recharge from canals and irrigation); 3 (Pakistan), 4 (India) *Upper Indus* (very high permeability, high storage; rainfall 500 – 1000 mma^{-1}, recharge from rainfall and canals); 5 *drier Uttar Pradesh* (very high permeability, high storage; rainfall 500 – 1000 mma^{-1}, recharge from rainfall and canals); 6 *wetter Uttar Pradesh* (very high permeability, high storage; rainfall 1000-2500 mma^{-1}, recharge from rainfall); 7 *Lower Ganges and Bengal basin* (very high permeability, high storage; rainfall 1000-2500 mma^{-1}, recharge from rainfall and rivers).

Additional longer term datasets were sought for the basin to help contextualise the WTR. Several historical long term records were collated from Pakistan and India, (Supplementary Table 4). Data were digitised from reports published in the 1970s and 1980s and matched to modern data monitoring boreholes.

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 GADM (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 (IBIS) in June 2002 and repeated in June 2012 [33] in conjunction with a statistical analysis of 3175 water level records in Punjab from 2003-2011 [34]. 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 CGWB published maps [35]. The district groundwater-level estimated from these available data In India and Pakistan were then checked against data in the WTR dataset. 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 1267 monitoring wells from the Bangladesh Water Development Board [36,37] was adapted to map mean annual groundwater-level trend at district level. The original Bangladesh Water Development Board dataset 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 [38] 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 4 countries: annual fall (m) >0.75, 0.25–0.75, 0.05 – 0.25, stable -0.02 - +0.02; and annual rise (m) 0.05 - 025). The WRT 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 basinwide groundwater storage changes. A further breakdown of the WTR data per region is shown in Supplementary Figure 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 datasets 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 summarised 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 [39]. The data were extracted and plotted for each Indian district. In Pakistan, the spatial work of Cheema [40] mapping groundwater for irrigation in 2007 was integrated for each district and compared to more recent national abstraction and irrigation data presented by the FAO [41]. Urban groundwater abstraction was estimated from various published sources [42]. For Bangladesh, district groundwater abstraction was derived from two recent groundwater models developed for Bangladesh using available data [26,43] and supplemented with specific information on groundwater abstraction for Dhaka [44]. For the Nepal Terai abstraction data do not exist and volumes were estimated from a published global irrigation assessment [45]. Abstraction assigned to each district within the IGB aquifer was converted to a spatially averaged depth of water in mm.

Groundwater chemistry

Mapping groundwater chemistry for the IGB alluvial aquifer system focussed 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, and most data refer to shallow groundwater (<200 m and often <100 m); spatial information on water quality variations was assigned to the full depth of the upper 200 m which represents the approximate thickness of the exploited aquifer. 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 and divided into four categories <500, 500-1000, 1000-2500, >2500 mg/L reflecting potential water use. The WHO has no official guidelines for TDS, but suggest that <1000 is generally acceptable for drinking water. Areas of elevated arsenic concentrations (>10µg/L) in shallow groundwater (< 200 m bgl) were determined by using a combination of available maps and national datasets, local datasets and published studies and 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 {46,47] The presence of Holocene deposits could be reliably mapped across the IGB, though organic-rich soils can be more locally variable. The IGB was therefore, divided into three categories: (1) elevated arsenic known to be widespread through detailed study; (2) elevated arsenic believed likely to occur given the geological setting and isolated studies; and (3) 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, parameterised 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 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 Figure 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 summarised as a confidence interval.

Data availability

The maps developed for abstraction, groundwater level trend, salinity and arsenic and groundwater storage are available are available 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 material.

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