Complexity of the Indo-Gangetic aquifer system revealed by *in situ* observations

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Groundwater abstraction from the transboundary Indo-Gangetic alluvial aquifer comprises 25% of global groundwater withdrawals. Over 15-million irrigation water-wells extract groundwater from the aquifer system and sustain agricultural productivity in Pakistan, India, Nepal and Bangladesh. Recent interpretations of satellite gravity data and global hydrological models indicate that current abstraction is unsustainable, [1,2,3] yet these large-scale interpretations are poorly constrained by ground observations and 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 water-quality, which reveal that degradation of groundwater quality poses a greater threat to sustained abstraction than depletion. We estimate the volume of groundwater in the upper 200 m of the aquifer to be more than 20 times the combined annual flow of the Indus, Brahmaputra and Ganges, but almost 60% is affected by salinity or hazardous arsenic concentrations. The water-table is near stable across 58% of the aquifer, falling in 33% and rising in 9% giving a net annual depletion from 2000-2012 of 6.8 ±2.6 km^3. Variations in rainfall, canal leakage and abstraction determine local groundwater accumulation and depletion, with large abstraction partially offset by induced recharge and reduced natural discharge. Recent depletion in northern India and Pakistan has also occurred within a much longer history of groundwater accumulation through canal leakage. *In situ* observations put recent large-scale evaluations in context: groundwater storage provides an effective buffer to seasonal and inter-annual variations in climate and surface water flows; localised water-quality degradation, groundwater depletion and accumulation require careful management to sustain groundwater use.

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 (2010 figures) and this volume continues to increase at 2–5 km^3/a [Supplementary Table 1], as farmers intensify agricultural production, and the proportion of water-intensive crops such as sugar cane and paddy rice are grown. Abstraction is unevenly distributed (Figure 1) yet is depended on as source of 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 as well as having an important depth dimension. 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. Leakage from this irrigation infrastructure has had a profound impact on the current quantity and quality of groundwater resources and is a significant factor governing its response to contemporary and future pressures. Increasing groundwater use for irrigation poses legitimate questions about the future sustainability of abstraction from the basin and future groundwater security of this region is 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 coarse scale of 400x400 km [1,2,3], These analyses have indicated 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] and focussed on the Indian states of Punjab, Haryana and Rajasthan. These studies are poorly constrained by ground-based observations; local field studies nonetheless provide partial insight into system dynamics. These include evidence of: declining groundwater levels [11,12,13], salinization of shallow groundwater [14,15] and increasing groundwater nitrate concentrations [16,17]. An important factor is the occurrence and mobilisation of geogenic arsenic in shallow groundwater across extensive areas of the aquifer in Bangladesh [18,19] 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 significant change to precipitation, river flows and groundwater recharge [20,21,22].

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 3652 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 salinity; 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 can form the basis for 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 the long-term trend is relatively stable throughout much of the basin, with some important exceptions. In areas of high groundwater abstraction in northwest India and the Punjab in Pakistan (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 [23]. 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 continuing leakage from canals and rivers.

Compiled data indicate substantial spatial variability over short distances (Figure 3b) in areas where the mean annual water-table is falling by >0.25 m/a. This variability can be explained by the dynamics of groundwater recharge within individual canal commands [24]. The water-table is often rising or stable at the head of a canal command where leakage is high and groundwater abstraction generally less. Towards the end of a canal command, less canal water is available for use and recharge, therefore 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 2b). 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 the IGB aquifer 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 and a priority for future monitoring. Also, much of the available information from the top 200 m is not depth specific, although there is growing evidence that stratification within the top 200 m is important throughout the aquifer [25].

Groundwater storage and water quality within the top 200 m of the aquifer were assessed from lithological data on specific yield, and 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 across the IGB aquifer and often stratified with depth. The two main concerns are salinity and arsenic, although other pollutants are present and most parts of the basin are at risk of 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 is estimated as having salinity greater than 1000 mg/L. A further 11,000 ± 5,000 km^3 of groundwater storage is affected by arsenic at toxic concentrations (Figure 4).

The origin of the saline groundwater is complex, formed by a variety of natural processes: saline intrusion, historic marine transgression, dissolution of evaporite layers and excessive evaporation of surface water or shallow groundwater. Salinity derived from these natural processes is exacerbated by the long term impact of irrigation and shallow water-tables. Only the lower Bengal basin subject to Quaternary marine influence [26] therefore, the widespread salinity in the Indus basin and drier parts of the Upper Ganges are almost entirely terrestrial in origin (Figure 4). The most likely mechanisms driving salinization in these areas are high evaporation from shallow water tables, irrigation or flooding and the mobilisation of deeper groundwater which has interacted with evaporite sequences. The distribution of evaporite deposits within the aquifer is confined to the Middle and Upper Ganges and the Indus and is largely governed by historical climate, with extended arid periods leading to their development. In the Bengal basin and Pakistan coast, salinization of groundwater is caused by both historical and current marine influence.

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 [18,19]. Less extreme arsenic concentrations, though still >10 µg/L, occur in other parts of the IGB, including Assam, India, southern Nepal, the Sylhet trough in eastern Bangladesh, and within Holocene sediments along the course of the Ganges and Indus river systems. Abstraction can impact arsenic mobilisation: recent research [27] 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 [28], but there is concern that high-capacity deep pumping may draw As down to levels in the BAS which are otherwise of good quality [29]. Despite this concern 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 6.8 km^3/a (range 4.1-9.4 km^3/a) with significant variation across the basin. The largest depletion occurred in areas of high abstraction and consumptive use in northern India (Punjab 2.3 km^3/a (range 1.5-3.1 km^3/a), Haryana 1.2 km^3/a (range 0.77-1.7 km^3/a) and Uttar Pradesh 1.2 km^3/a (range 0.75-1.7 km^3/a) and northern Pakistan (Punjab State 1.9 km^3/a (range 1.0-2.4 km^3/a). In the Lower Indus, within the Sindh, groundwater is accumulating at a rate of 0.3 km^3/a (range 0.16-0.46 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 (±2 mm). Our estimates of annual groundwater depletion in northern India (4.7 ± 1.7 km^3/a) differ significantly from those of Rodell and others [1] who estimated 18 km^3/a depletion in Punjab, Haryana and Rajasthan using GRACE data from within the same period. However, much of the depletion estimated in their study occurs outside the main IGB aquifer, in the desert of Rajasthan, which should be considered a separate aquifer system, 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 2]. 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 [11,27] show that abstraction can markedly increase recharge, reduce natural discharge, and induce younger water deeper into the aquifer. As Figure 2 demonstrates, leakage from canals has historically been a highly significant source of recharge, and even today several 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. Such detailed data can help to uncover the hydrological processes at work and also inform the management of groundwater abstraction in a sustainable manner.

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; water chemistry; and groundwater storage. In addition, a dataset of 3652 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 2). A range of time periods, length and frequency of record were 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 were within the time period 1975 – 2013. This reduced the dataset to 3810. Much of the 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 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 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 3652, which formed the final water-table records dataset (WTR).

In addition to WTR, additional longer term datasets were sought for the basin to help contextualise the shorter term records. Several historical long term records were collated from Pakistan and India, and several others digitised from graphs written in the 1970s and 80s (Supplementary Table 2).

Map of annual groundwater-level trend

To develop the map of mean annual trend in water-table for the period 2000-2012, the WTR was combined with existing national maps and databases of groundwater level variation for Pakistan and India (Supplementary Table 3). For Bangladesh a recently published map of water-table variation was used, and for Nepal where no regional maps were available, the WTR data were given priority. Using this new combined map as a base, data from the WTR was used to refine and distribute the water-table classes to increase the precision of the maps particularly in the areas ±0.25 m. The systematic data-bins developed across the 4 countries were: annual fall (m) >1, 0.25–1.0, 0.05–0.0; and annual rise (m) 0-0.05, 0.05 -025). Summary data for the WTR database were then calculated for each data-bin.

Groundwater abstraction

A basin wide map of 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 and Bangladesh which covered the period 2008 to 2013 (Supplementary Table 1). For the Nepal Terai where no other data exist, abstraction was estimated from a global irrigation assessment [32]. Abstraction assigned to each district within the IGB aquifer was converted to a spatially averaged depth of water in mm.

Groundwater chemistry

Groundwater chemistry for the IGB alluvial aquifer system was mapped by focussing on the distribution of elevated concentrations of salinity and arsenic in groundwater, the two most significant water quality issues within the basin. 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 4). 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. Elevated arsenic concentrations (>10µg/L) in shallow groundwater (< 200 m bgl) was mapped 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 4). The IGB was divided into three categories: (1) elevated arsenic known to be widespread through detailed study; (2) believed likely to occur given the geological setting and isolated studies; and (3) likely to occur only in isolated areas given the geological setting.

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 [33] 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. The 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 grain 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 [33]. For each typology the likely range and specific yield was established. The 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. The range presented represents uncertainty in specific yield which dominates the potential uncertainty.

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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 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.

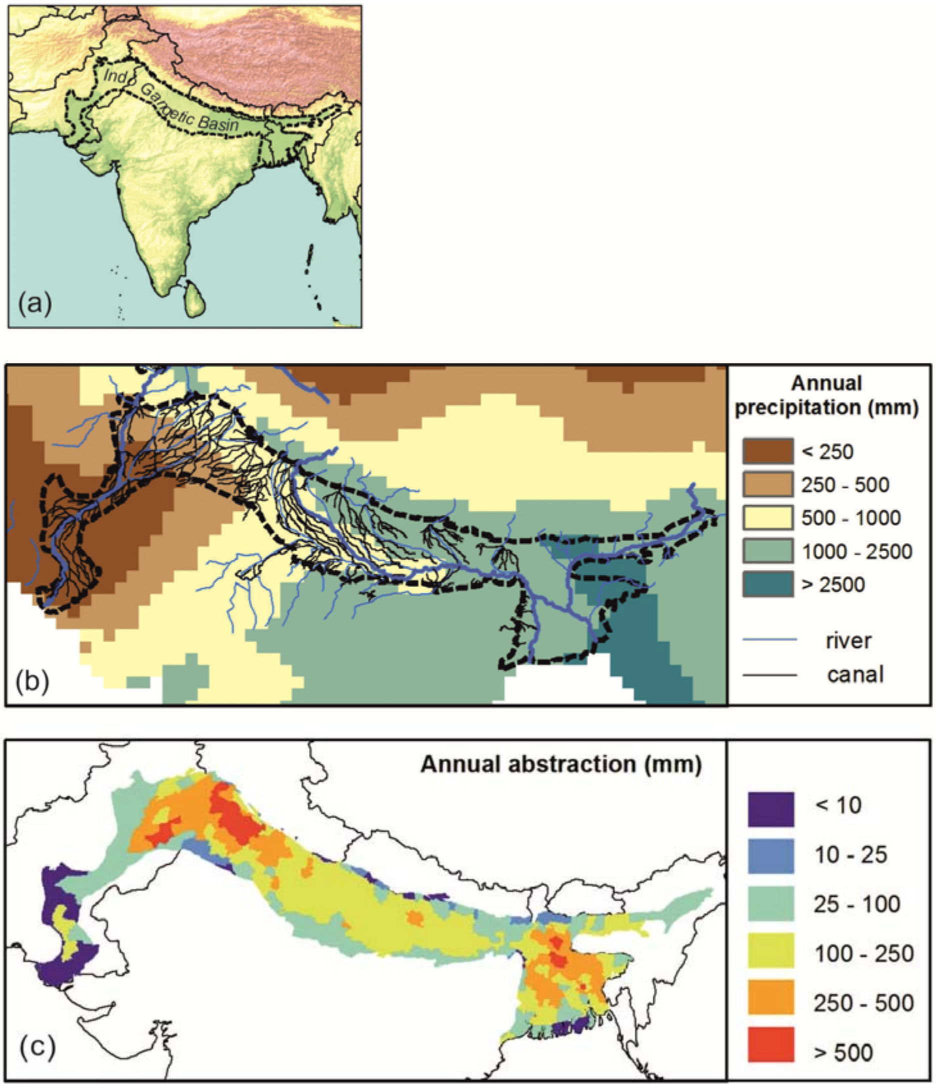

Figure 1 (a) location of the Indo Gangetic Basin alluvial aquifer system; (b) mean annual precipitation 1950 – 2010 [9], rivers and major canal distribution; and (c) estimated mean annual groundwater abstraction in 2010, showing the high groundwater abstraction in north west India, northern Pakistan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

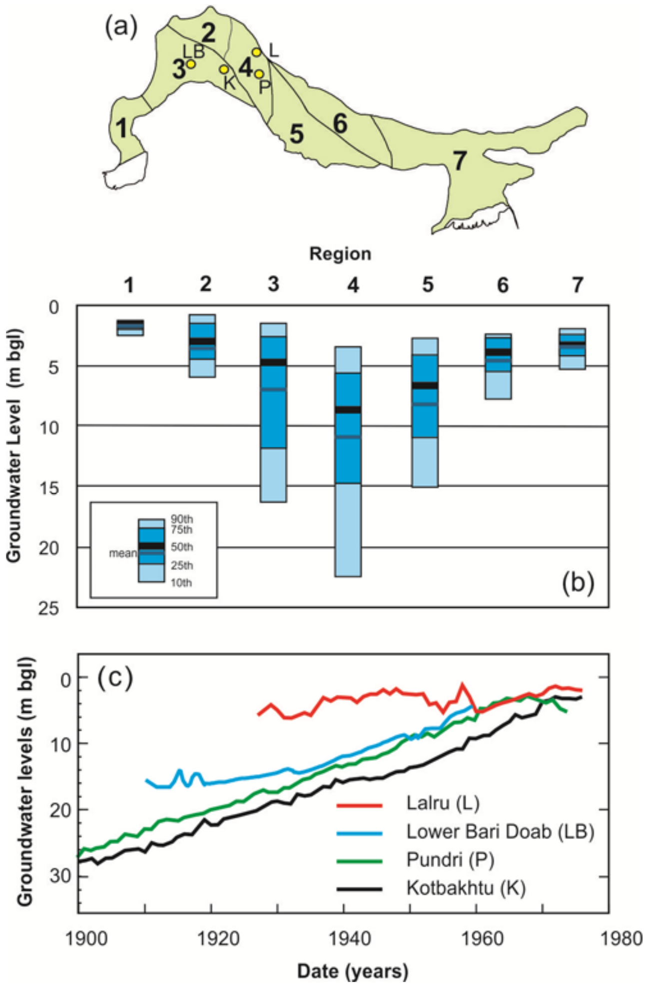

Figure 2. Water-table variations across the IGB aquifer system: (a) location of analysis regions (divided by aquifer and climate) and long-term monitoring sites, 1 Sindh; 2,4 upper Indus, 3 middle Indus; 5 drier Uttar Pradesh; 6 wetter Uttar Pradesh; 7 Lower Ganges and Bengal basin; (b) data from the 3652 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 water level (c) long term hydrographs for four indicator wells, LB, P and K are in areas with canals, and L is not within a canal command area.

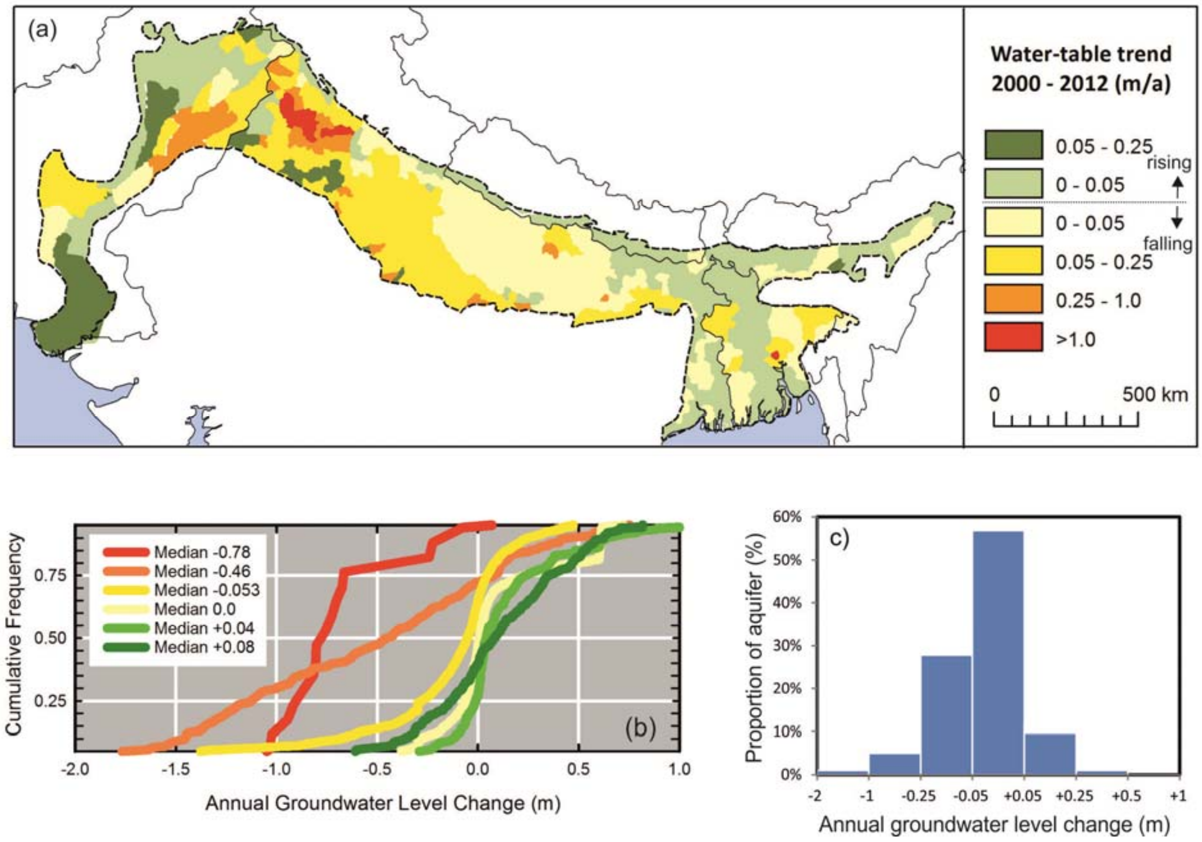

Figure 3. Annual change in water-table estimated from regional datasets and validated with 3652 multi-year records for the period 2000 - 2012: (a) map of mean annual change across the basin during the period 2000-2012; (b) cumulative frequency distributions for each water-table category demonstrating 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; and (c) proportion of the aquifer with rising or falling groundwater levels, 58% of the aquifer has near stable groundwater levels.

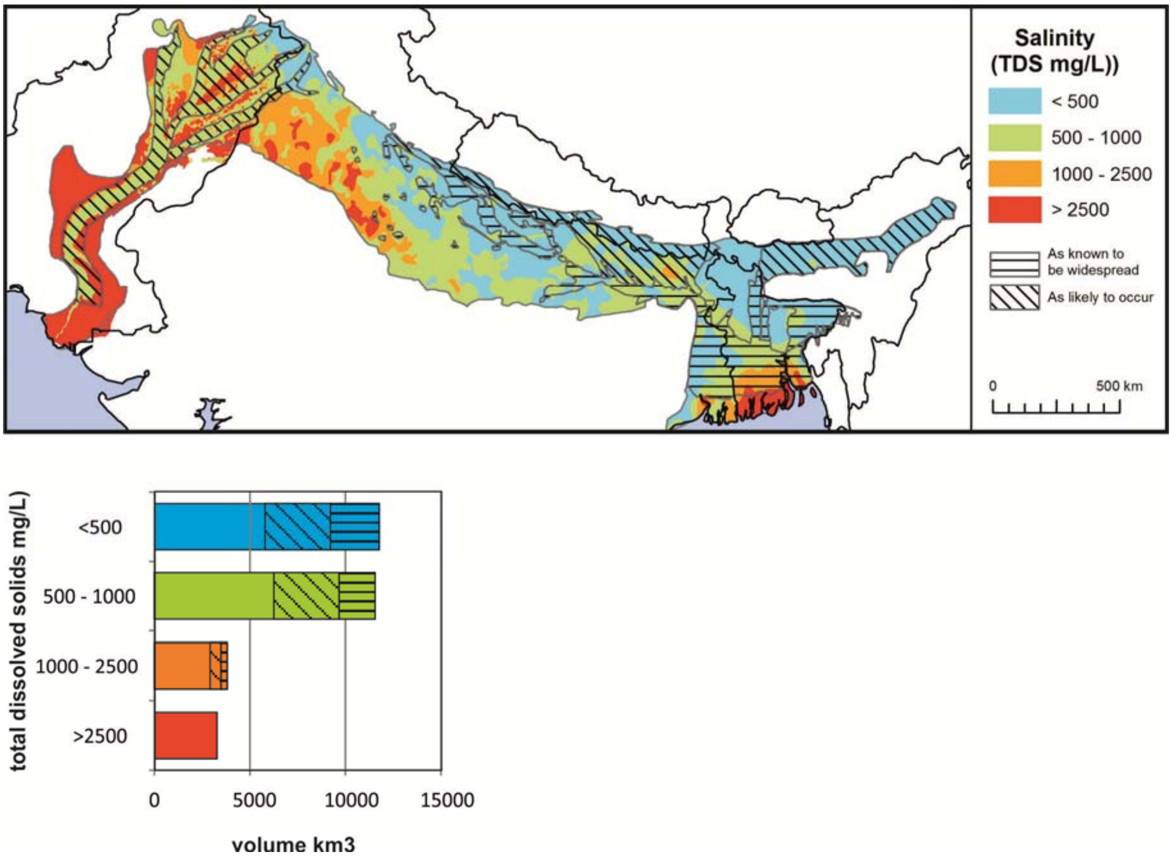

Figure 4. Groundwater quality in the IGB aquifer system: (a) salinity measured as total dissolved solids in the groundwater and areas where arsenic is known to be widespread, or thought likely to occur; and (b) the volume of the water in the top 200 m of the aquifer by quality, total volume is 30,000 km^3 ±14,000 km^3.