

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

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35 **Groundwater abstraction from the transboundary Indo-Gangetic alluvial aquifer**  
36 **comprises 25% of global groundwater withdrawals. Over 15-million irrigation water-wells**  
37 **extract groundwater from the aquifer system and sustain agricultural productivity in**  
38 **Pakistan, India, Nepal and Bangladesh. Recent interpretations of satellite gravity data and**  
39 **global hydrological models indicate that current abstraction is unsustainable, [1,2,3] yet**  
40 **these large-scale interpretations are poorly constrained by ground observations and lack**  
41 **the spatio-temporal resolution required to govern groundwater effectively [4 ,5]. Here we**  
42 **report new evidence from high-resolution *in situ* records of groundwater-levels,**  
43 **abstraction and water-quality, which reveal that degradation of groundwater quality**  
44 **poses a greater threat to sustained abstraction than depletion. We estimate the volume**  
45 **of groundwater in the upper 200 m of the aquifer to be more than 20 times the combined**  
46 **annual flow of the Indus, Brahmaputra and Ganges, but almost 60% is affected by salinity**  
47 **or hazardous arsenic concentrations. The water-table is near stable across 58% of the**  
48 **aquifer, falling in 33% and rising in 9% giving a net annual depletion from 2000-2012 of 6.8**  
49 **±2.6 km<sup>3</sup>. Variations in rainfall, canal leakage and abstraction determine local**  
50 **groundwater accumulation and depletion, with large abstraction partially offset by**  
51 **induced recharge and reduced natural discharge. Recent depletion in northern India and**  
52 **Pakistan has also occurred within a much longer history of groundwater accumulation**  
53 **through canal leakage. *In situ* observations put recent large-scale evaluations in context:**  
54 **groundwater storage provides an effective buffer to seasonal and inter-annual variations**  
55 **in climate and surface water flows; localised water-quality degradation, groundwater**  
56 **depletion and accumulation require careful management to sustain groundwater use.**

57

58 The Indo Gangetic Basin (IGB) alluvial aquifer system is one of the world's most important  
59 freshwater resources. Formed by sediments eroded from the Himalayas and redistributed by the  
60 Indus, Ganges and Brahmaputra river systems, the IGB aquifer forms a flat fertile plain across  
61 Pakistan, northern India, southern Nepal and Bangladesh (Figure 1). Fifteen to twenty million water-  
62 wells abstract an estimated 205 km<sup>3</sup>/a (2010 figures) and this volume continues to increase at 2–5  
63 km<sup>3</sup>/a [Supplementary Table 1], as farmers intensify agricultural production, and the proportion of  
64 water-intensive crops such as sugar cane and paddy rice are grown. Abstraction is unevenly  
65 distributed (Figure 1) yet is depended on as source of drinking water for rural and urban populations  
66 across the full extent of the IGB. The aquifer system is usually represented as a single category on  
67 hydrogeological maps [6]. However, in practice the system is complex and heterogeneous with large  
68 spatial differences in permeability, storage, recharge and water chemistry as well as having an  
69 important depth dimension. This complexity strongly influences how each part of the aquifer  
70 responds to stresses [7]. The IGB is home to the largest surface water irrigation system in the world,  
71 constructed during the 19<sup>th</sup> and early 20<sup>th</sup> century to redistribute water from the Indus and Ganges  
72 through a canal network >100,000 km long. Leakage from this irrigation infrastructure has had a  
73 profound impact on the current quantity and quality of groundwater resources and is a significant  
74 factor governing its response to contemporary and future pressures. Increasing groundwater use for  
75 irrigation poses legitimate questions about the future sustainability of abstraction from the basin  
76 and future groundwater security of this region is a major social-political concern [8].

77 Recent discussion of water security has been dominated by interpretations of remotely-sensed  
78 gravity data from the GRACE mission gathered at a coarse scale of 400x400 km [1,2,3], These  
79 analyses have indicated a general reduction in terrestrial water storage in northern India and  
80 Pakistan since data became available in 2002, equivalent to approximately 40 mm/a [1] with annual  
81 variability, [10] and focussed on the Indian states of Punjab, Haryana and Rajasthan. These studies  
82 are poorly constrained by ground-based observations; local field studies nonetheless provide partial  
83 insight into system dynamics. These include evidence of: declining groundwater levels [11,12,13],

84 salinization of shallow groundwater [14,15] and increasing groundwater nitrate concentrations  
85 [16,17]. An important factor is the occurrence and mobilisation of geogenic arsenic in shallow  
86 groundwater across extensive areas of the aquifer in Bangladesh [18,19] and throughout other parts  
87 of the basin primarily where Holocene deposits dominate. Additional uncertainty in future  
88 groundwater security has been introduced by forecasts of climate change and the potential for  
89 significant change to precipitation, river flows and groundwater recharge [20,21,22].

90 Here we present for the first time an analysis of the status of groundwater across the IGB alluvial  
91 aquifer based entirely on *in situ* measurements. We use a statistical analysis of multiyear  
92 groundwater-level records from 3652 water-wells and a compilation and interpretation of existing  
93 high resolution spatial datasets and studies within Pakistan, India, Nepal and Bangladesh to assess:  
94 (1) groundwater-level variations; (2) groundwater salinity; and (3) groundwater storage within the  
95 top 200 m of the aquifer. In doing so, we have developed several new transboundary spatial  
96 datasets that give new insight to the aquifer system and can form the basis for improved regional  
97 modelling and water governance.

98 We find that the water-table within the IGB alluvial aquifer is typically shallow (< 5 m below ground  
99 surface) and the long-term trend is relatively stable throughout much of the basin, with some  
100 important exceptions. In areas of high groundwater abstraction in northwest India and the Punjab in  
101 Pakistan (Figure 2) the water-table can be >20 m bgl and in some locations is falling at rates of > 1  
102 m/a (Figure 3). In areas of equivalent high irrigation abstraction within Bangladesh, the average  
103 water-table remains shallow (<5 m bgl) due to greater direct recharge and high capacity for induced  
104 recharge. Groundwater levels are deep and falling beneath many urban areas, and particularly in  
105 large groundwater dependant cities such as Lahore, Dhaka and Delhi [23]. Shallow and rising water-  
106 tables are found in the Lower Indus, parts of the lower Bengal basin and in places throughout the  
107 IGB aquifer as a consequence of continuing leakage from canals and rivers.

108 Compiled data indicate substantial spatial variability over short distances (Figure 3b) in areas where  
109 the mean annual water-table is falling by  $>0.25$  m/a. This variability can be explained by the  
110 dynamics of groundwater recharge within individual canal commands [24]. The water-table is often  
111 rising or stable at the head of a canal command where leakage is high and groundwater abstraction  
112 generally less. Towards the end of a canal command, less canal water is available for use and  
113 recharge, therefore groundwater abstraction is greater and the water-table declines. Groundwater  
114 level data from the early 20<sup>th</sup> century in India and Pakistan, show that the recent observations of  
115 falling water-table in some areas are part of a much longer history (Figure 2b). Rising groundwater  
116 levels and water-logging were a major concern from 1875, and a consequence of leakage from the  
117 major canal construction projects which redistributed water from rivers to land. As a result, during  
118 much of the 20<sup>th</sup> century the IGB aquifer accumulated groundwater at the expense of river flow to  
119 the ocean. It is important to note that in contrast to the wealth of data available for the shallow  
120 water-table, data on deep groundwater-levels below 200 m is absent or sparse throughout the IGB  
121 and a priority for future monitoring. Also, much of the available information from the top 200 m is  
122 not depth specific, although there is growing evidence that stratification within the top 200 m is  
123 important throughout the aquifer [25].

124 Groundwater storage and water quality within the top 200 m of the aquifer were assessed from  
125 lithological data on specific yield, and national surveys on water quality. The total volume in the top  
126 200 m of aquifer is  $30,000 \pm 14,000$  km<sup>3</sup> (Figure 4). This amounts to 20 – 30 times the combined  
127 mean annual flow in the rivers within the basin ( $1,000 - 1,500$  km<sup>3</sup>/a). Groundwater quality is highly  
128 variable across the IGB aquifer and often stratified with depth. The two main concerns are salinity  
129 and arsenic, although other pollutants are present and most parts of the basin are at risk of  
130 contamination from nitrate and faecal pathogens. Of the  $30,000$  km<sup>3</sup> of groundwater storage  
131 estimated in the basin  $7,000 \pm 3,000$  km<sup>3</sup> is estimated as having salinity greater than 1000 mg/L. A  
132 further  $11,000 \pm 5,000$  km<sup>3</sup> of groundwater storage is affected by arsenic at toxic concentrations  
133 (Figure 4).

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

146 Arsenic-rich groundwater occurs in chemically reducing, grey-coloured, Holocene sediments, mostly  
147 restricted to groundwater in the uppermost 100 m across the floodplains in the southern Bengal  
148 Basin where arsenic is commonly present at  $>100 \mu\text{g/L}$  [18,19]. Less extreme arsenic concentrations,  
149 though still  $>10 \mu\text{g/L}$ , occur in other parts of the IGB, including Assam, India, southern Nepal, the  
150 Sylhet trough in eastern Bangladesh, and within Holocene sediments along the course of the Ganges  
151 and Indus river systems. Abstraction can impact arsenic mobilisation: recent research [27] reveals  
152 that intensive abstraction of shallow groundwater can flush aqueous As from the aquifer; irrigation  
153 pumping protects deeper groundwater in some instances, by creating a hydraulic barrier [28], but  
154 there is concern that high-capacity deep pumping may draw As down to levels in the BAS which are  
155 otherwise of good quality [29]. Despite this concern retardation is expected to delay vertical  
156 migration by centuries [28].

157 Estimated trends in groundwater storage for the IGB alluvial aquifer, derived from *in situ*  
158 measurements of water-table variations (Figure 3) and estimates of specific yield derived across the

159 basin, indicate a net average annual groundwater depletion within the period 2000-2012 of 6.8  
160 km<sup>3</sup>/a (range 4.1-9.4 km<sup>3</sup>/a) with significant variation across the basin. The largest depletion  
161 occurred in areas of high abstraction and consumptive use in northern India (Punjab 2.3 km<sup>3</sup>/a  
162 (range 1.5-3.1 km<sup>3</sup>/a), Haryana 1.2 km<sup>3</sup>/a (range 0.77-1.7 km<sup>3</sup>/a) and Uttar Pradesh 1.2 km<sup>3</sup>/a (range  
163 0.75-1.7 km<sup>3</sup>/a) and northern Pakistan (Punjab State 1.9 km<sup>3</sup>/a (range 1.0-2.4 km<sup>3</sup>/a). In the Lower  
164 Indus, within the Sindh, groundwater is accumulating at a rate of 0.3 km<sup>3</sup>/a (range 0.16-0.46 km<sup>3</sup>/a),  
165 which has led to increased waterlogging of land and significant reduction in the outflow of the River  
166 Indus [13]. Across the rest of the IGB, changes in groundwater storage are generally modest ( $\pm 2$   
167 mm). Our estimates of annual groundwater depletion in northern India ( $4.7 \pm 1.7$  km<sup>3</sup>/a) differ  
168 significantly from those of Rodell and others [1] who estimated 18 km<sup>3</sup>/a depletion in Punjab,  
169 Haryana and Rajasthan using GRACE data from within the same period. However, much of the  
170 depletion estimated in their study occurs outside the main IGB aquifer, in the desert of Rajasthan,  
171 which should be considered a separate aquifer system, not actively recharged by rainfall, only canal  
172 leakage.

173 *In situ* observations also provide evidence of the strong link between groundwater and surface water  
174 within the basin. Given the high volume of abstraction in parts of the basin, the measured rate of  
175 water-table decline is too small to derive from direct rain-fed recharge alone [see Supplementary  
176 Figure 2]. Although this discrepancy could be attributed to errors and uncertainty in developing  
177 abstraction and water-table datasets from *in situ* data, field studies in the IGB [11,27] show that  
178 abstraction can markedly increase recharge, reduce natural discharge, and induce younger water  
179 deeper into the aquifer. As Figure 2 demonstrates, leakage from canals has historically been a highly  
180 significant source of recharge, and even today several studies estimate canal leakage to be  
181 approximately 50% [30]. Groundwater recharge in the IGB is not static, or a function of rainfall  
182 alone. It is highly dynamic, and influenced by abstraction, river flows and canal engineering. The  
183 complex and dynamic nature of the IGB alluvial aquifer revealed by this study highlights the  
184 fundamental importance of regular and distributed *in situ* measurements of groundwater-levels and

185 water quality. Such detailed data can help to uncover the hydrological processes at work and also  
186 inform the management of groundwater abstraction in a sustainable manner.

187

## 188 **Methods**

189 Four separate transboundary spatial datasets were developed for the IGB across Pakistan, India,  
190 Nepal and Bangladesh using ground-based data: water-table trend per annum; groundwater  
191 abstraction; water chemistry; and groundwater storage. In addition, a dataset of 3652 multi-year  
192 water-table records was developed.

### 193 *Developing the multiyear water-table record (WTR) dataset*

194 More than 10,000 individual time series of groundwater-level records were collated from the IGB  
195 across India, Nepal, Bangladesh and Pakistan from numerous sources (Supplementary Table 2). A  
196 range of time periods, length and frequency of record were present within the dataset and a quality  
197 assurance process was undertaken to develop the final dataset. The inclusion criteria were: a  
198 minimum length of 7 years of records; at least two measurements per year at high and low water-  
199 table; and records were within the time period 1975 – 2013. This reduced the dataset to 3810.

200 Much of the data (82%) are entirely within the time period 2000-2012 with 11% from 1989-2000, 6%  
201 1993-2005 and 1% from 1975-2012. Data from outwith the period 2000-2012 were used to give  
202 information in areas where no other data were available. For each individual time series the linear  
203 trend in mean, maximum and minimum groundwater level was calculated using a linear regression  
204 model. These values were estimated by fitting a model to the full data set with separate trend  
205 parameters (slope and intercept) for each borehole time series. The dataset was first explored for  
206 skewness and outliers removed by applying Tukey's fences [31]). ANOVA indicated that all effects in  
207 the model are significant (adjusted  $R^2$  0.96) indicating the occurrence of temporal trends which



208 differ between wells. Minimum, maximum and mean groundwater-level were also calculated for  
209 each borehole for the total length of record. After the statistical treatment of the data and removal  
210 of individual outliers, the number of usable time series was reduced to 3652, which formed the final  
211 water-table records dataset (WTR).

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

#### 215 *Map of annual groundwater-level trend*

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

#### 225 *Groundwater abstraction*

226 A basin wide map of groundwater abstraction was developed by combining the complete available  
227 district data for India for the year 2010 with a combination of local and published datasets for  
228 Pakistan and Bangladesh which covered the period 2008 to 2013 (Supplementary Table 1). For the  
229 Nepal Terai where no other data exist, abstraction was estimated from a global irrigation assessment  
230 [32]. Abstraction assigned to each district within the IGB aquifer was converted to a spatially  
231 averaged depth of water in mm.

232 *Groundwater chemistry*

233 Groundwater chemistry for the IGB alluvial aquifer system was mapped by focussing on the  
234 distribution of elevated concentrations of salinity and arsenic in groundwater, the two most  
235 significant water quality issues within the basin. Groundwater salinity was mapped by compiling  
236 existing information of groundwater chemistry and specific electrical conductance from national and  
237 regional surveys across the four countries (Supplementary Table 4). Salinity was represented as  
238 total dissolved solids expressed in mg/L and divided into four categories <500, 500-1000, 1000-2500,  
239 >2500 mg/L reflecting potential water use. The WHO has no official guidelines for TDS, but suggest  
240 that <1000 is generally acceptable for drinking water. Elevated arsenic concentrations (>10µg/L) in  
241 shallow groundwater (< 200 m bgl) was mapped by using a combination of available maps and  
242 national datasets, local datasets and published studies and an understanding of the distribution of  
243 Holocene deposits in the basin (Supplementary Table 4). The IGB was divided into three categories:  
244 (1) elevated arsenic known to be widespread through detailed study; (2) believed likely to occur  
245 given the geological setting and isolated studies; and (3) likely to occur only in isolated areas given  
246 the geological setting.

247 *Groundwater storage*

248 Groundwater storage in the top 200 m was calculated using an estimate of the effective thickness  
249 and specific yield (drainable porosity) of the aquifer. We estimated these properties using  
250 hydrogeological typologies [33] developed from an interpretation of the sedimentology of the basin.  
251 The interpretation incorporated a review of geological and sedimentological literature,  
252 parameterised with information on grain size and modes of deposition. For much of the IGB, the  
253 thickness is fully 200 m, reduced to 100 m in the piedmont area. The deeper confined regions of the  
254 aquifer (200 – 350 m) in the southern Bengal Basin were not included in this assessment. Specific  
255 yield was mapped across the basin using available grain size distribution for the top 200 m of  
256 alluvium, and validated with several key hydrogeological studies of specific yield undertaken in

257 different parts of the basin [33]. For each typology the likely range and specific yield was  
258 established. The groundwater storage was then calculated using this range of estimates and the  
259 effective thickness of aquifer. Annual trends in groundwater storage were calculated using the  
260 estimates of specific yield for the IGB and the annual trend in groundwater level for the period 2000  
261 – 2012. The range presented represents uncertainty in specific yield which dominates the potential  
262 uncertainty.

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#### 352 **Author Contributions**

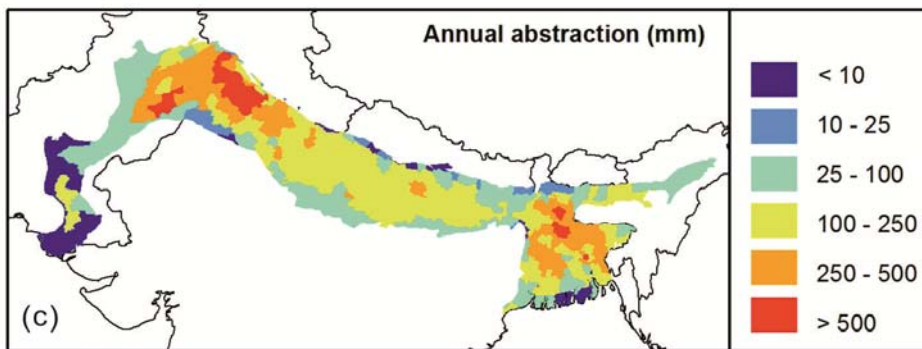
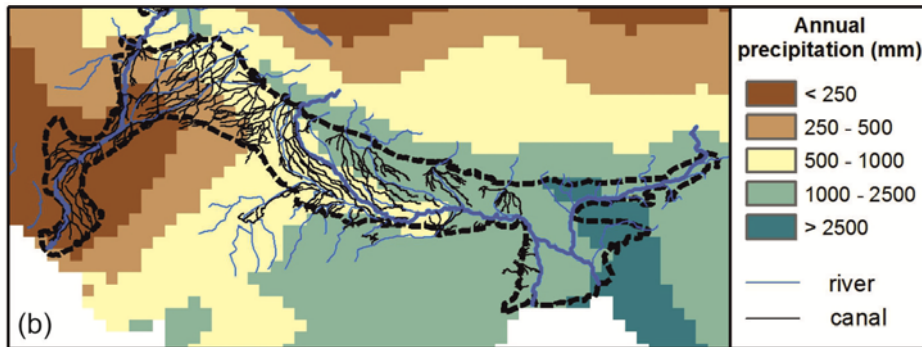
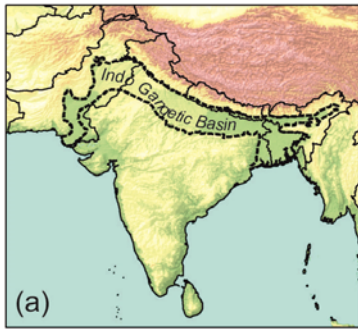
353 AM developed the transboundary maps and prepared the first draft of the manuscript, HB prepared  
354 the times series dataset and developed maps, KA, WB, RT and MS, developed datasets and  
355 interpretation for Bangladesh, LS, MM, AD and SY developed datasets and interpretation for Nepal,  
356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

#### 360 **Competing Financial Interests statement**

361 There are no competing financial interests.

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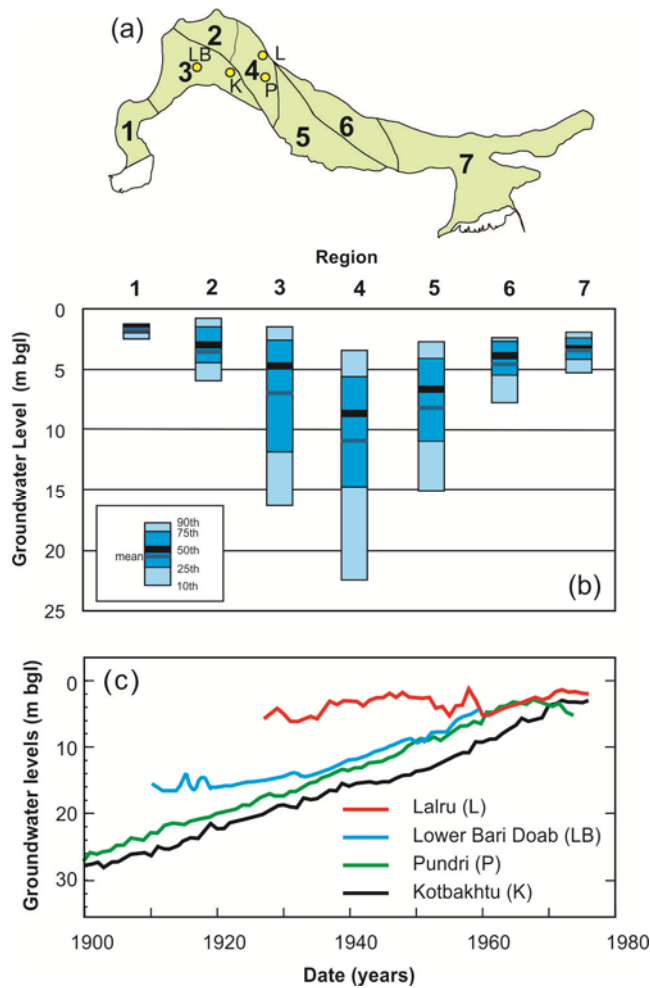


364

365 *Figure 1 (a) location of the Indo Gangetic Basin alluvial aquifer system; (b) mean annual precipitation*  
 366 *1950 – 2010 [9], rivers and major canal distribution; and (c) estimated mean annual groundwater*  
 367 *abstraction in 2010, showing the high groundwater abstraction in north west India, northern*  
 368 *Pakistan and Central and Northern Bangladesh. Total groundwater abstraction from the aquifer is*  
 369 *205 km<sup>3</sup>, approximately 25% of the global total (Supplementary Table 1).*

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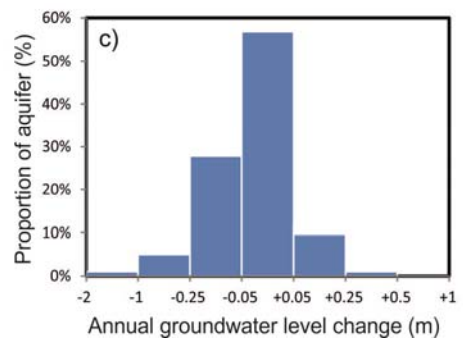
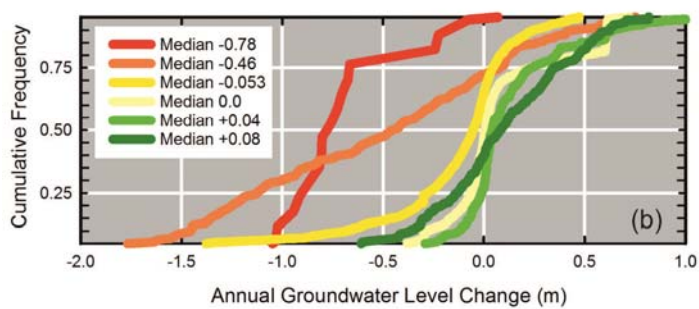
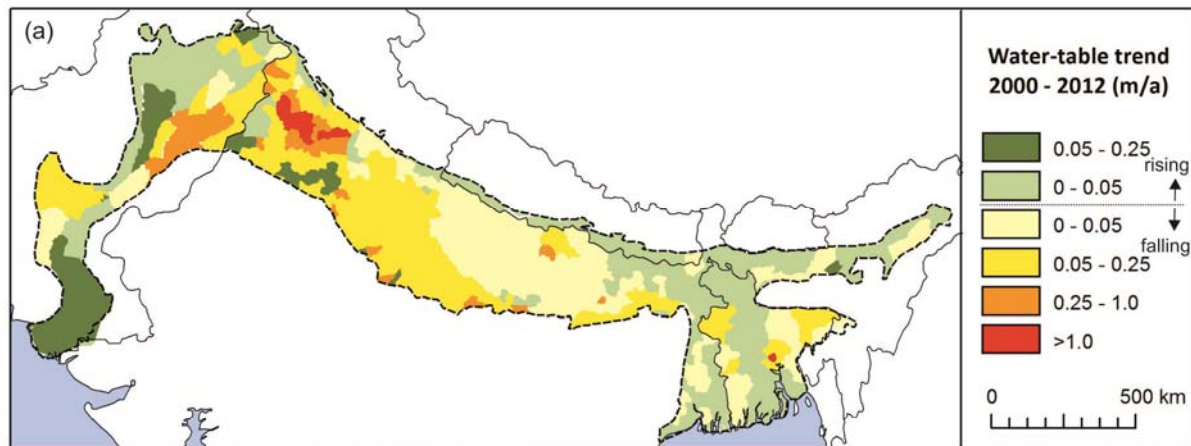




371

372 *Figure 2. Water-table variations across the IGB aquifer system: (a) location of analysis regions*  
 373 *(divided by aquifer and climate) and long-term monitoring sites, 1 Sindh; 2,4 upper Indus, 3 middle*  
 374 *Indus; 5 drier Uttar Pradesh; 6 wetter Uttar Pradesh; 7 Lower Ganges and Bengal basin; (b) data*  
 375 *from the 3652 monitoring points showing mean water-table depths in individual wells for the period*  
 376 *2000 - 2012; areas with high abstraction and lower rainfall show deepest groundwater levels and a*  
 377 *wide range in measured water level (c) long term hydrographs for four indicator wells, LB, P and K*  
 378 *are in areas with canals, and L is not within a canal command area.*

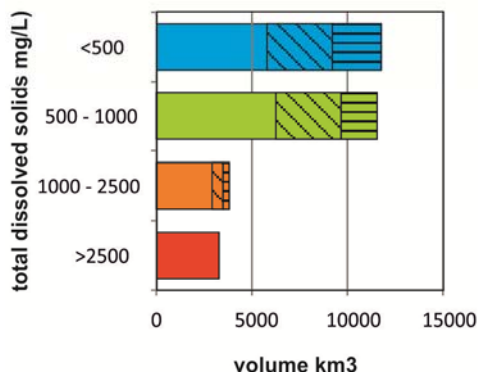
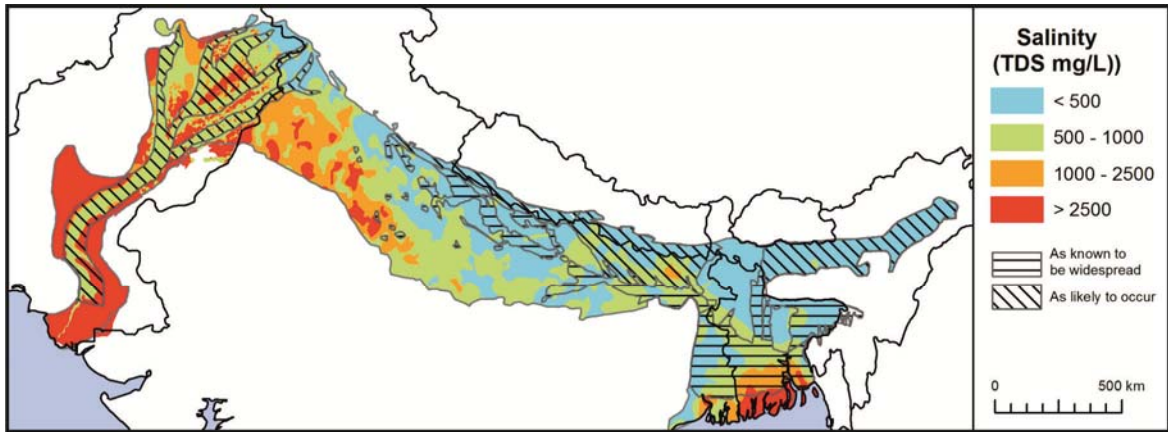
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380

381 *Figure 3. Annual change in water-table estimated from regional datasets and validated with 3652*  
 382 *multi-year records for the period 2000 - 2012: (a) map of mean annual change across the basin*  
 383 *during the period 2000-2012; (b) cumulative frequency distributions for each water-table category*  
 384 *demonstrating the low spatial variability in areas with annual changes close to zero, and the high*  
 385 *variability where water levels are falling by more than 0.25 m per year; and (c) proportion of the*  
 386 *aquifer with rising or falling groundwater levels, 58% of the aquifer has near stable groundwater*  
 387 *levels.*

388



389

390 *Figure 4. Groundwater quality in the IGB aquifer system: (a) salinity measured as total dissolved*  
 391 *solids in the groundwater and areas where arsenic is known to be widespread, or thought likely to*  
 392 *occur; and (b) the volume of the water in the top 200 m of the aquifer by quality, total volume is*  
 393 *30,000 km<sup>3</sup> ±14,000 km<sup>3</sup>.*

394