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GROUNDWATER SCIENCE PROGRAMME

OPEN REPORT OR/14/070

Deep groundwater in the Bengal Mega-Delta: new evidence of aquifer hydraulics and the influence of intensive abstraction

RG Taylor[1], WG Burgess[1], M Shamsudduha[1], A Zahid[2], DJ Lapworth[3], K Ahmed[4], AMukherjee[5], S Nowreen[6]

[1] University College London (UCL), UK

[2] Bangladesh Water Development Board, Bangladesh

[3] British Geological Survey, UK

[4] Dhaka University, Bangladesh

[5] Indian Institute of Technology (Kharagpur), India

[6] Bangladesh University of Engineering & Technology, Dhaka, Bangladesh

Keywords

Bengal Aquifer System, arsenic, salinity, groundwater age indicators, climate change, recharge.

Front cover

Sampling water from a well in the Sundarbans region (Gabura) of coastal Bangladesh [Dan Lapworth].

Bibliographical reference

TAYLOR, RG, BURGESS, WG, SHAMSUDDUHA, M, ZAHID, A, LAPWORTH, DJ, AHMED, K, MUKHERJEE, A, NOWREEN, S., 2014. Deep groundwater in the Bengal Mega-Delta: new evidence of aquifer hydraulics and the influence of intensive abstraction. *British Geological Survey Open Report*, OR/14/070. 24pp.

Keyworth, Nottingham British Geological Survey 2014

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British Geological Survey offices

BGS Central Enquiries Desk

Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA

Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

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Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE

Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
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Foreword

This report is an output from the DFID funded project *Groundwater resilience to climate change and abstraction in the Indo-Gangetic basin.*

Groundwater resilience to climate change and abstraction in the Indo-Gangetic basin is a two-year (2012-14) research project strengthening the evidence-base linking groundwater resources, climate variability and abstraction in the Indo-Gangetic basin. This project has been funded by UK aid from the UK Government, and led by the British Geological Survey, however the views expressed do not necessarily reflect the UK Government's official policies. The project has two main aims:

- To develop a strategic overview assessment of the occurrence and status of groundwater resources in the Indo-Gangetic basin and develop a map of groundwater typologies spanning the groundwater system
- To strengthen the evidence-base linking groundwater resources, climate and abstraction through a series of four targeted case studies in the basin.

The project team involves researchers from the British Geological Survey, IIT Kharagpur, ISET-Nepal, ISET International, Meta-Meta, National Institute of Hydrology (Roorkee), Overseas Development Institute, University College London, University of Dhaka and Bangladesh Water Development Board.

For more information:

http://www.bgs.ac.uk/research/groundwater/international/

This report is the product of a study by University College London (UCL) in collaboration with the British Geological Survey (BGS), Bangladesh Water Development Board (BWDB), Dhaka University (DU, Bangladesh), Indian Institute of Technology (IIT Kharagpur, India), and Bangladesh University of Engineering and Technology (BUET, Bangladesh). The report describes the findings of a Case Study on *Deep groundwater in the Bengal Mega-Delta: new evidence of aquifer hydraulics and the influence of intensive abstraction*, a component of the BGS research programme 'Groundwater resources in the Indo-Gangetic Basin: resilience to climate change and pumping'. The Case Study focusses on the security of deep groundwater in the coastal region of the Bengal Aquifer System (BAS) of the Ganges-Brahmaputra-Meghna (GBM) delta. Regionally, deep groundwater in BAS has acquired strategic importance as a secure water resource for tens of millions of inhabitants of Bangladesh and West Bengal. Population increase, irrigation demand and climate change will combine to increase the stress on the resource in the future. It is hoped that the outcomes of this Case Study will enable a more robust evaluation of the response of deep groundwater in the GBM delta region to increasing development and to climate change.

Acknowledgements

Several individuals in Bangladesh and India contributed significantly to this project. Their assistance was critical not only in the collection of field observations but also in providing local advice and knowledge. We would particularly like to thank Kamrul Islam (Bangladesh Water Development Board, currently Institute of Water Modelling, Dhaka, Bangladesh), Mainul Islam (Dhaka University, Bangladesh), Sukhen Goswami (Dhaka University) and Soumendra Bhanja (IIT Kharapgur).

Contents

Summary

This report describes the findings of a Case Study on *Deep groundwater in the Bengal Mega-Delta: new evidence of aquifer hydraulics and the influence of intensive abstraction*, a component of the BGS research programme 'Groundwater resources in the Indo-Gangetic Basin: resilience to climate change and pumping'. The report focusses on the security of deep groundwater in the coastal region of the Bengal Aquifer System (BAS) of the Ganges-Brahmaputra-Meghna (GBM) delta. It addresses the principal points of uncertainty concerning deep groundwater recharge and vulnerability to ingress of arsenic as the aquifer system responds to the combined stresses of climate change and anthropogenic influences.

The two primary research activities are first described: depth-specific groundwater monitoring, and analysis of changes in rainfall intensity throughout the 21st century. Allied research is reported, on the security of alternative deep groundwater pumping strategies, shallow groundwater dynamics in relation to arsenic concentration, and groundwater–surface water relationships. A summary of field activities and field data collected is provided.

The preliminary findings are presented as depth-specific profiles of groundwater heads and chemistry from nested monitoring stations instrumented under the study, and as projected intensification of rainfall in Bangladesh over the period 2070–2099 relative to 1961–1990. These findings, together with the outcomes of allied research on deep groundwater pumping strategies and shallow groundwater dynamics, improve understanding of BAS at the depths where abstraction is rapidly accelerating, the hydraulic connectivity between the deep and shallow parts of the aquifer system, and the likely impact of climate change.

Our analysis justifies the cautious expansion of deep groundwater pumping in Bangladesh under a robust regime for regulating abstractions and monitoring groundwater levels and groundwater quality. Further questions are identified which will need to be addressed to support management of the deep groundwater resource and further development of policy.

1 Motivation and research questions

The Ganges-Brahmaputra-Meghna (GBM) delta region of the Indo-Gangetic Basin is dependent upon groundwater to satisfy enormous demand for domestic and agricultural water supplies. The twin contexts of this study are: the strategic importance of deep groundwater in the Bengal Aquifer System (BAS) as a secure water resource for tens of millions of inhabitants of Bangladesh and West Bengal; and the uncertain response of the hydrological system of the GBM delta to changes in climate and large-scale anthropological interventions. In the GBM delta area, 'deep groundwater' (>150 m depth in the sediments of the BAS) is increasingly being developed by public authorities and private abstractors as a water source free of excessive arsenic which pervades shallow basin sediments (Figure 1). Installation of deep wells for domestic water supply has become a popular, practical and economic mitigation response to the arsenic crisis. Regionally, deep groundwater has acquired strategic importance as a secure water resource for tens of millions of inhabitants of Bangladesh and West Bengal, India. In the future there may also be pressure on deep groundwater from the enormous irrigation demand across the rural floodplain areas that is currently met by groundwater from shallow and intermediate depths (<100 m bgl). There remains, however, considerable uncertainty in the security of the BAS deep groundwater resource including: (1) the ability of recharge to balance heavy abstraction of deep groundwater and prevent excessive groundwater-level decline; (2) the vulnerability of deep groundwater throughout the floodplains to the ingress of arsenic drawn down from shallow levels and, in coastal regions, to the ingress of salinity; and (3) the impacts of climate change comprising not only sea-level rise (SLR) but also the potential intensification of rainfall.

In terms of the vulnerability of deep groundwater, the amount and timing of vertical leakage induced by deep pumping is determined by the fundamental hydraulic structure and properties of the aquifer sediments. Little is known, however, of the hydraulic character of the BAS at the depths where abstraction is rapidly accelerating, nor of the hydraulic continuity between the shallow and deeper depths of the aquifer system. Investigative modelling studies, though valuable, are constrained by a lack of data at depth in the aquifer system to enable robust model calibrations. Age-dating of deep groundwater has, to date, been piecemeal and unrelated to the municipal foci of deep pumping. The '*Deep groundwater in the Bengal Mega-Delta: new evidence of aquifer hydraulics and the influence of intensive abstraction*' case study addresses the need to develop a greater understanding of the response of deep groundwater in the GBM delta region to increasing development and to climate change, and its future security. Our results are expected to contribute directly to development of policy for deep groundwater development by Governmental authorities. In this report, we differentiate between primary research activity funded directly through the *Groundwater resilience to climate change and abstraction in the Indo-Gangetic Basin* project and allied research activity, funded separately (*e.g.* EPSRC), that further informs our results.

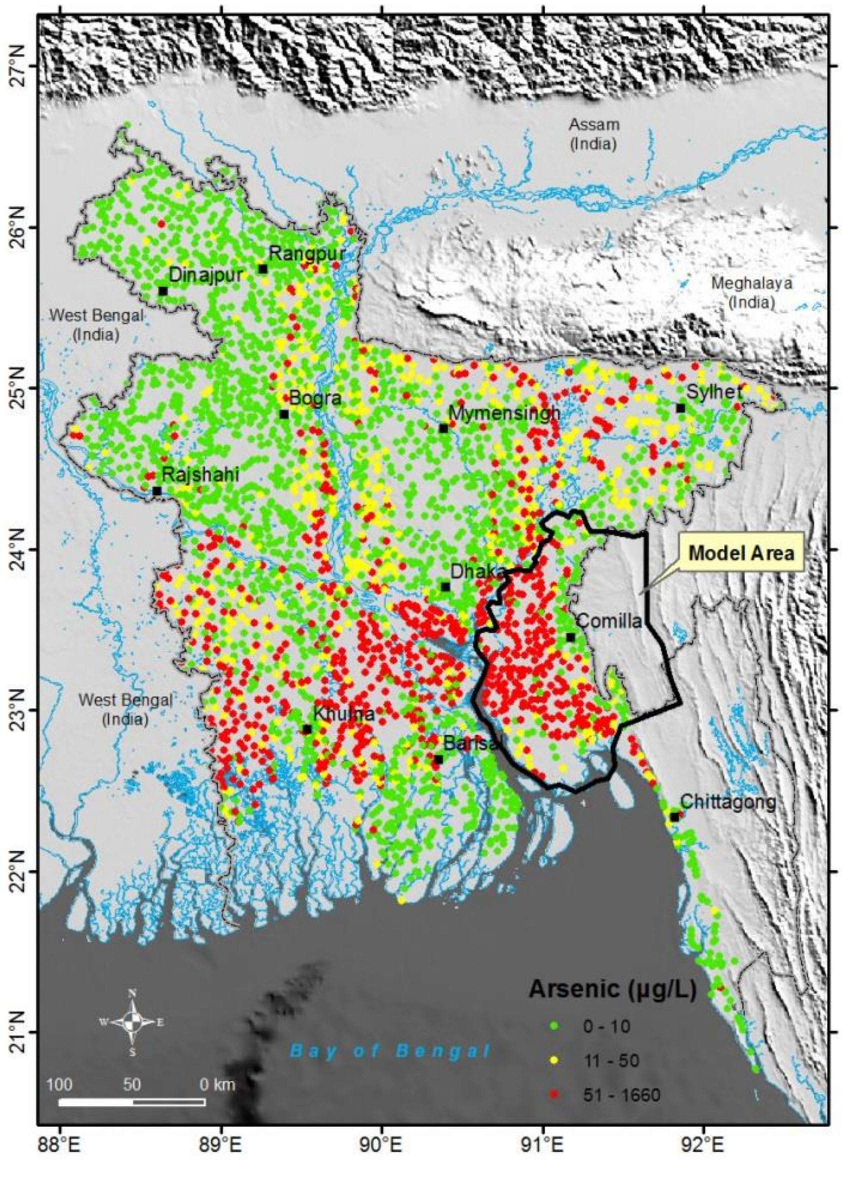

Figure 1. Map showing the spatial distribution of groundwater arsenic in Bangladesh [data from the National Hydrochemical Survey in Bangladesh[3]]

2 Description of research activities and study areas

2.1 PRIMARY RESEARCH ACTIVITY

2.1.1 Depth-specific groundwater monitoring in the coastal region of the Bengal Basin

The establishment of nested monitoring stations at shallow, intermediate and deep groundwater depths in collaboration with the Bangladesh Water Development Board, Dhaka University and IIT Kharagpur was designed to improve understanding of the hydraulic character of the BAS and hydraulic continuity between the shallow and deeper depths of the aquifer system. Four pairs of sites were selected in a W-E transect across the delta region (Figure 2) where hydraulic and hydrochemical studies were conducted to investigate the nature and scale of impacts of deep pumping, and vertical hydraulic continuity. Each pair of sites included an inland site (50 to 100 km from the coast) with a history of deep groundwater pumping (Kamgachhi, Khulna, Barisal) and/or a history of previous research (Khulna, Kachua), and a coastal site very proximate (<5 km) to the sea or tidal channel. The 4 pairs of sites (8 study locations in total) in Figure 2 are: Kamgachi / Digha (West Bengal); Khulna / Gabura (SW Bangladesh), Barisal / Kuakata (south-central Bangladesh), and Laksmipur / Kachua (SE Bangladesh). Through sampling and the application of automated 'divers' (pressure-transducer dataloggers), we have developed hydrochemical profiles of groundwater in the BAS including inorganic constituents and parameters (*e.g.* arsenic (As), specific conductivity (SEC)), environmental isotopes (O and H stable isotopes), and residence-time indicators (CFCs, SF_6, ^{14}C - planned) and compiled a high-resolution (hourly) hydraulic dataset. This research is strongly complemented by a more extensive programme of manual, weekly groundwater-level monitoring in nested piezometers at 42 sites situated across coastal and southern Bangladesh led by Dr. Anwar Zahid at the Bangladesh Water Development Board[1].

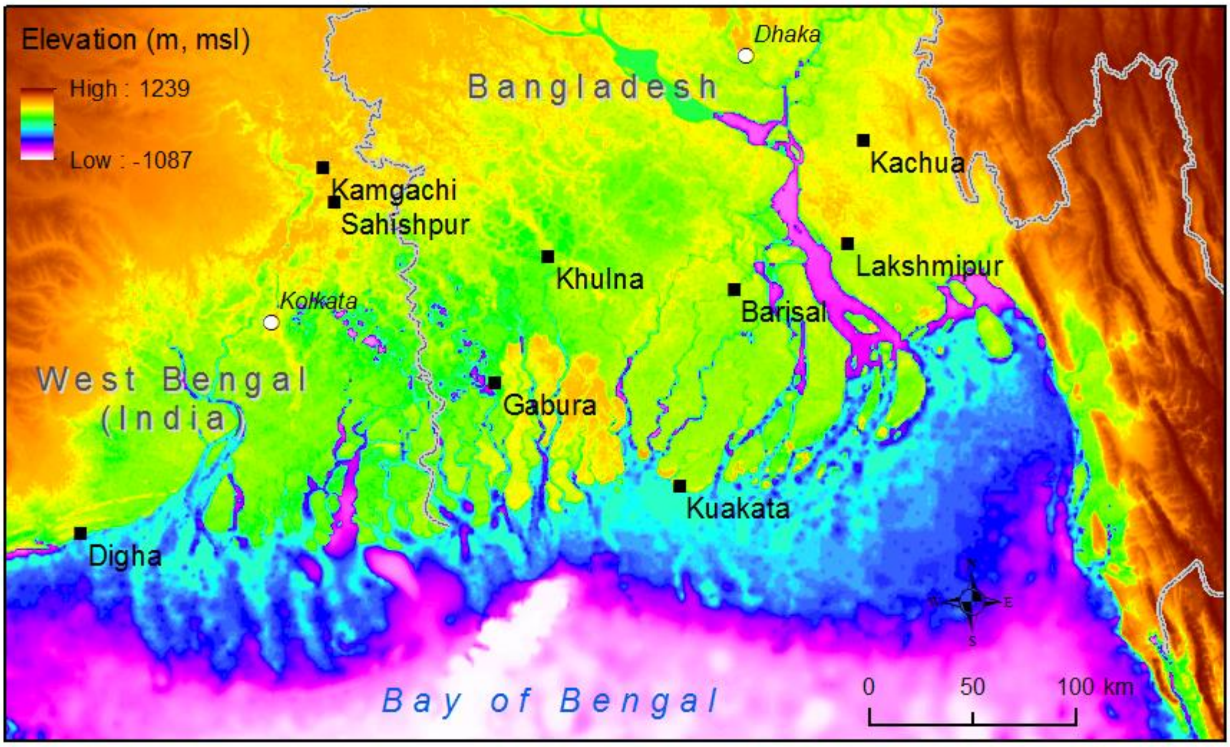

Figure 2. Map showing the location of the multi-level groundwater monitoring sites in Bangladesh and West Bengal, India. [Background image shows the SRTM digital elevation model, source: USGS.]

[1] BWDB 2013. Hydrogeological study and mathematical modelling to identify sites for installation of observation well nests, Main Report. Bangladesh Water Development Board and Institute of Water Modelling.

2.1.2 Analysis of projected changes in rainfall intensity as a result of climate change in the IGB Delta Region

Analysis of historical climate over a 5° box centered on the IGB Delta Region of Bangladesh (Figure 3) employed gridded monthly precipitation at 0.5° resolution from the GPCC product version 5 from 1955 to 2009. Climate-change projections were obtained for the late 21st century (2070-2099) from multi-model ensembles (MMEs) compiled under the third (CMIP3) and fifth (CMIP5) Coupled Model Intercomparison Projects contributing to the 4th and 5th Assessment Reports (AR4 & AR5) of the Intergovernmental Panel on Climate Change (IPCC). In total, the MMEs contain data from 23 General Circulation Models (GCMs) for the CMIP3 dataset and 21 GCMs for the CMIP5 archive, of which 8 are newly introduced Earth System Models (ESMs). Use of data from a single greenhouse-gas emission scenario (Special Report on Emissions Scenario A1B) from the CMIP3 collection, and two emission Representative Concentration Pathway scenarios from the CMIP5 collection (RCP4.5 and RCP8.5) is also made.

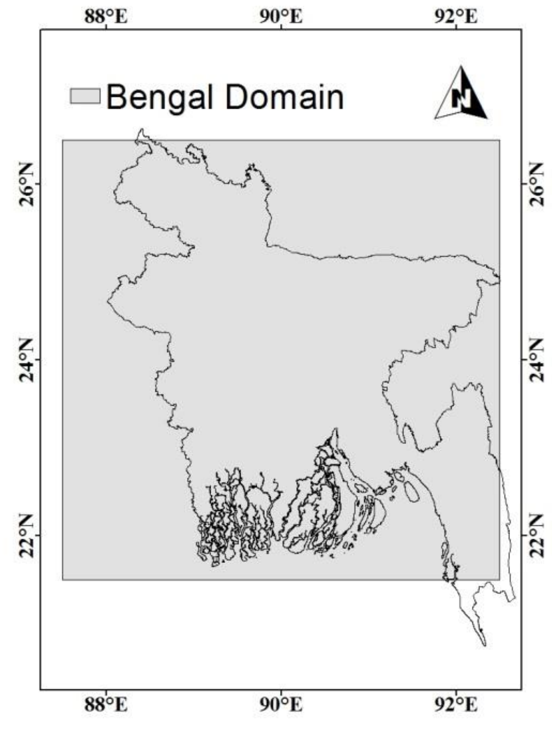

Figure 3. Domain comprising a 5° box over Bangladesh for which CMIP3 (AR4) and CMIP5 (AR5) climate projections were analysed.

2.2 ALLIED RESEACH ACTIVITY

2.2.1 Shallow groundwater dynamics and their relationship to arsenic concentrations in Bangladesh

The impact of very intensive use of shallow groundwater on groundwater levels (storage) across Bangladesh including the delta region has been rigorously assessed using both piezometry and Gravity Recovery And Climate Experiment (GRACE) satellite data[2]. Localised studies of arsenic

[2] Shamsudduha *et al*. 2009. Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna Delta. *Hydrology and Earth System. Sciences,* 13: 1-13. Shamsudduha *et al*., 2012. Monitoring groundwater storage changes in the Bengal Basin: validation of GRACE measurements. *Water Resources Research,* 48: W02508.

(As) in Bangladesh have, to date, generated inconsistent outcomes regarding the impact of intensive groundwater use on As concentrations in shallow (≤50 m bgl) groundwater. To evaluate associations between arsenic concentrations in shallow groundwater and intensive abstraction of shallow groundwater, we constructed generalised regression models (GRMs) to describe observed spatial variations in As concentrations both (i) nationally, and (ii) regionally within Holocene deposits where As concentrations in shallow groundwater are generally high (>10 µg L^{-1}). We exploited hydraulic data compiled at UCL from several sources in Bangladesh and the national-scale survey of As concentrations in shallow groundwater in 1999 conducted by the BGS and Department for Public Health Engineering (DPHE) in Dhaka[3].

2.2.2 Groundwater – surface water connections from river transects of groundwater level and salinity

Salinity is a widespread problem in shallow groundwater in the coastal region of Bangladesh, but there has been little systematic study of its origin and interaction with fresh groundwater. A BWDB programme[1] has explored connections between shallow groundwater and surface water in cross-river transects of groundwater level and salinity in the coastal region. Here, river channels have very little fresh water flow but act as conduits for tidal flow originating in the Bay of Bengal. Very many distributaries and small tidal channels interconnect the large rivers. Five boreholes to 100 m depth were installed along each river transect to monitor of groundwater level and salinity over a 12 month period, 2013-2014, in the study of groundwater – surface water connections. Data are in the process of being compiled by BWDB. As a result, we do not at this time specifically report on findings in section 5.

3 Field activities

Field activities in the Delta Region of Bangladesh and West Bengal (India) occurred as follows:

03-04/2013 Installation of 24 water level (pressure) and 8 barometric pressure loggers at 8 sites

04-05/2013 Sampling of nested piezometer stations - sortie 1

11/2013 Downloading of automated loggers for 6-month record

03/2014 Sampling of nested piezometer stations - sortie 2

05/2014 Downloading of automated loggers for 12-month record

4 Field data collected

New observational field data include:

Groundwater chemistry: samples from multiple depths at 8 locations (Table 1) analysed for inorganic constituents including arsenic (As), environmental isotopes (O and H stable isotopes), and residence-time indicators (CFCs, SF_6, ^{14}C - planned)

Groundwater head: hourly groundwater (and barometric) pressure records from multiple depths (except Digha, West Bengal) at 8 locations (Table 1)

Groundwater salinity: large-scale survey conducted by project collaborators (BWDB) provides a new regional delineation of shallow groundwater salinity in the coastal region of Bangladesh (Figure 4).

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[3] BGS & DPHE 2001. Arsenic Contamination of Groundwater in Bangladesh, Vol. 2. Final Report, BGS Technical Report WC/00/19.

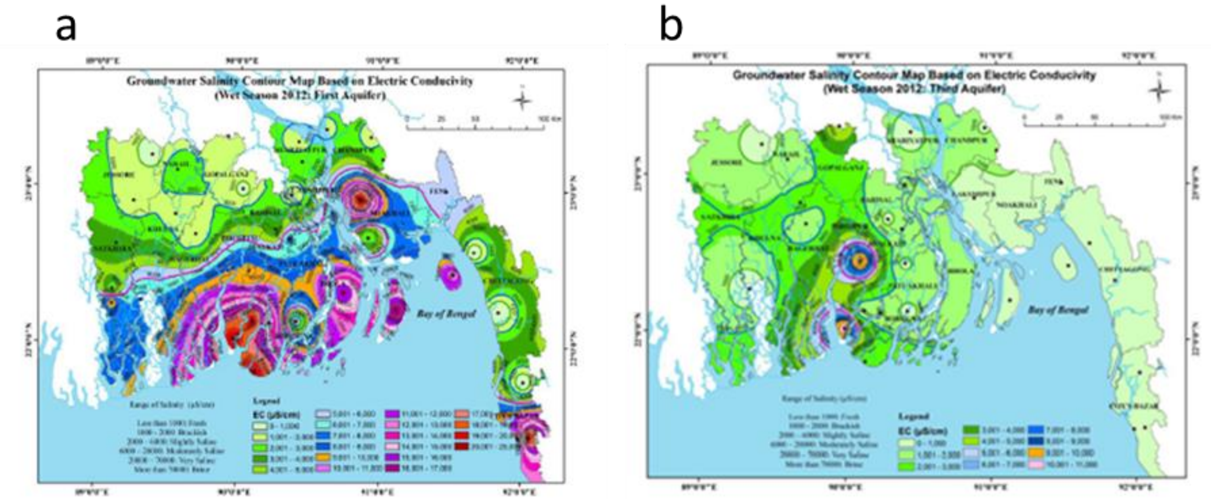

Figure 4. Contoured salinity in (a) the 'shallow (first) aquifer', and (b) the 'deep (third) aquifer' in coastal Bangladesh (from Zahid et al. 2013. Distribution of Groundwater Salinity and Its Seasonal Variability in the Coastal Aquifers of Bengal Delta, Book Chapter Nine in Adaptation to the Impact of Climate Change on Socio-economic Conditions of Bangladesh (edited by Zahid et al.), pp. 170-193.

Table 1. Overview of high-frequency (hourly) hydraulic monitoring since March/April 2013 and depth specific sampling in 2013 and 2014.

Site	Depth (m)	Monitoring	Sampling
Kachua	25	head, barometric	May, 2013
Bangladesh	165	head	
	280	head	
Laksmipur	91	head, barometric	May, 2013
Bangladesh	152	head	
	244	head	
Barisal	105	head, barometric	May, 2013
Bangladesh	151	head	
	236	head	
Kuakata (Kalapara)	122	head, barometric	May, 2013
Bangladesh	180	head	
	268	head	
Khulna	61	head, barometric	March, 2014
Bangladesh	164	head	
	323	head	
Gabura	67	head, barometric	March, 2014
Bangladesh	116	head	
	212	head	
Kamgachi	17	head, barometric	March, 2014
West Bengal	60	head	
	100	head	
Sahishpur West Bengal	37	head	March, 2014
Digha	250	head, barometric	to be sampled
West Bengal	250	head	

Preliminary findings

4.1 EVIDENCE FROM NESTED MONITORING STATIONS: DEPTH-SPECIFIC PROFILES OF GROUNDWATER HEADS AND CHEMISTRY

4.1.1 Groundwater heads

Groundwater heads were monitored using automatically recording pressure transducers installed in nested piezometers that represent an in-kind project contribution by the Bangladesh Water Development Board. At each site, records have been collected at three depths in vertical profile to maximum depth up to 320 m between May 2013 and June 2014 (Table 1). A selection (one coastal, one inland) of initial results is illustrated in Figure 5.

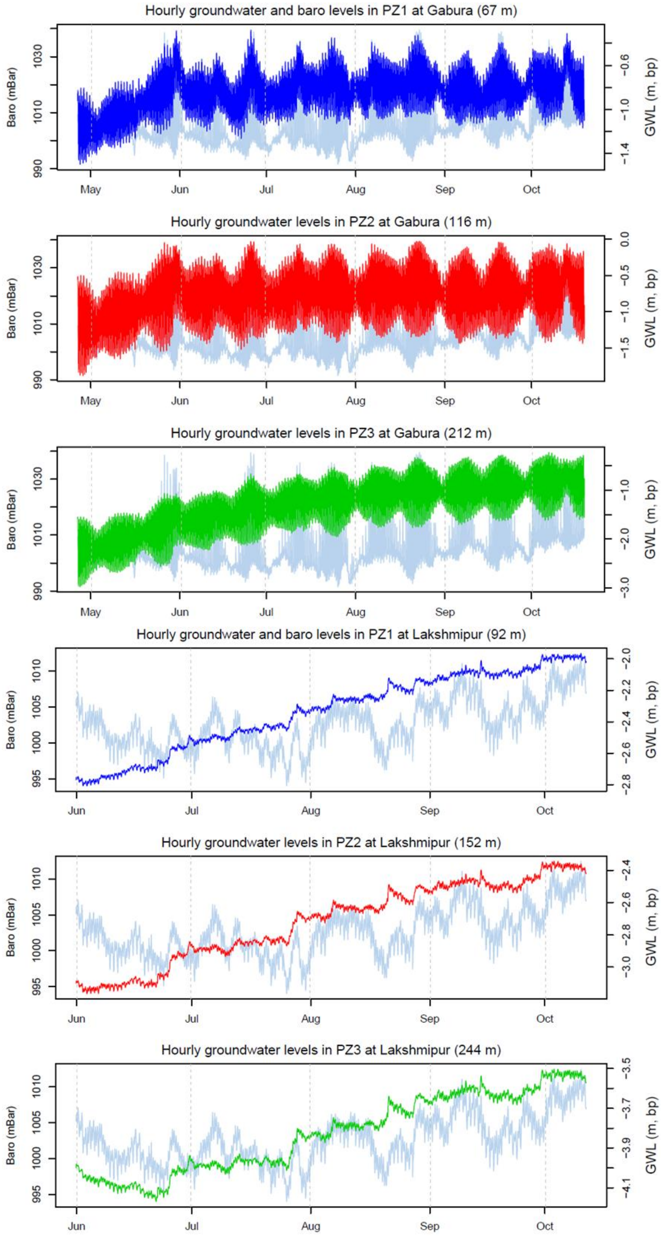

Figure 5. Groundwater head records in vertical profile and barometric pressure from Gabura (coastal site) and Lakshmipur (inland site) – note raw data require additional corrections for salinity. Depth values (m) in the plot titles indicate the depth below datum for the piezometers. The barometric data is shown as a pale blue line.

Vertical hydraulic gradients consistent with regional gravitational flow in the BAS are over-printed by the effects of intensive pumping, where it occurs. Vertically upward hydraulic gradients reflecting regional groundwater discharge are restricted to extreme coastal locations. Transient variations in deep groundwater head, remote from the effects of pumping, are dominated by the elastic response of the aquifer sediments to surface loading: periodic (tidal) loading in the vicinity of tidal water bodies (Figure 6), and episodic loading by terrestrial surface water during the monsoon season. In most records, episodic deflections of groundwater head in the order of 0.1 m and up to 0.5 m, near simultaneous with depth, are clearly resolvable. These deflections are several times larger than previously published results[4] of passive piezometric monitoring at 300 m depth.

The high susceptibility of the BAS sediments to compaction reduces the barometric effect, which is obscured by the larger scale impacts of groundwater pumping, and surface loading. Inland, where tidal loading is absent, small amplitude earth tide responses are ubiquitous in the background signal. At greater than 100 m depth, we interpret the seasonal recovery and recession in groundwater heads to be a record of annual changes in terrestrial water storage, largely independent of groundwater flow.

These results have important implications for management of the deep groundwater resources. In most hydrogeological environments, groundwater flow models are calibrated against measured groundwater heads. This study shows that for the Bengal Aquifer System, the sensitivity of deep groundwater heads to loading means that deep groundwater levels are not valid for calibration of uncoupled models of transient groundwater flow since rising heads are not indicators of recharge in this environment and falling heads do not indicate aquifer drainage.

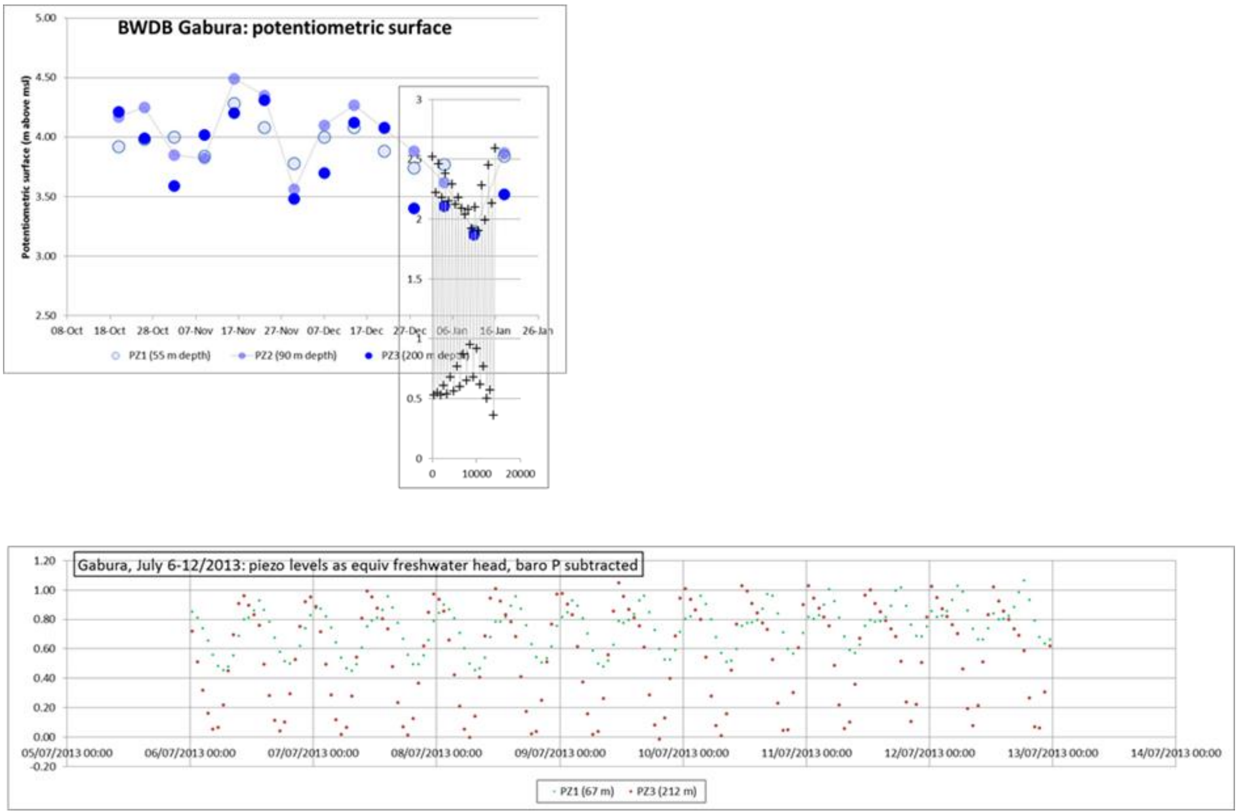

Figure 6. Groundwater head recorded in piezometers between 67 and 212 m depth, Gabura (southern Bangladesh), 2012 – 2013. Note correspondence with monthly tidal cycle consistent with surface mechanical loading (top), and the semi-diurnal tidal periodicity with phase shift between 67 m and 212 m depth (bottom).

[4] Reported in confined sandstones from Kansas (USA): Sophocelous *et al.*, 2006. A rainfall loading response recorded at 300 meters depth: Implications for geological weighing lysimeters. *Journal of Hydrology* 319: 237-244.

4.1.2 Groundwater chemistry

As shown in Figure 7, two anthropogenic tracers CFC-12 and SF_6 provide consistent age profiles through the BAS at the eight monitoring sites. The differences in absolute % modern values, for waters with only a small proportion of tracer generally greater than 50 mbgl, are an artefact of the analytical sensitivity and precision of the two methods (see Figure 7 caption for details). SF_6 is present in modern recharge at $fmol \cdot L^{-1}$ concentrations, CFCs are 3 orders of magnitude higher at $pmol \cdot L^{-1}$ concentrations.

Shallow groundwater, less than 50 mbgl, shows a range of % modern water with 0% at Kachua, 3% at Lakshmipur, 6% at Kuakata and Kamgachhi and >10% at Khulna and Sahishpur. Shallow sites were not available at Barisal but these are likely to be >10% since this was observed at this site in groundwater at 100 mbgl. Overall, slight declines in % modern CFC-12 with depth for groundwater below 50 mbgl (Figure 7a) are detectable at Khulna, Barisal and Lakshmipur with high historical rates of pumping. These trends are not, however, clearly evident in the % modern SF_6 results (Figure 7b).

Two public supply sites in Khulna with contrasting historical pumping regimes but in close proximity (<200 m bgl) to the BDWB monitoring site, were sampled at a depth of 290m (Figure 7) for comparison. There is a noteworthy anomaly for one of these two sites where there is evidence of a significantly higher component of modern recharge (>15%) in both CFC-12 and SF_6 results. Although both sites have been used since the early 1980s, the site with a higher component of modern recharge has been pumped on a 16 h cycle compared to a 7h cycle for the other site. Tracer differences are corroborated by stable isotope data that show distinct signatures in the two deep sites (Figure 8a). These observations strongly indicate vertical connectivity between the shallower and deeper depths of the BAS at this site that has most likely been induced by enhanced pumping.

Figure 7c reveals a widespread salinity at coastal sites, most notably at depths shallower than 200 mbgl. At some sites (*e.g.* Kuakata, Kachua), salinity is also a problem at depths of 270 to 280 mbgl where SEC is approaching or in excess of 2000 $\mu S \cdot cm^{-1}$. Figure 7d (note log scale on x axis) shows a decline in arsenic with depth from >100 $\mu g \cdot L^{-1}$ at shallow sites (<50 mbgl) to <5 $\mu g \cdot L^{-1}$ - below the WHO guideline value for drinking-water (10 $\mu g \cdot L^{-1}$) - at deeper sites (>100 mbgl). Exceptions occur at Barisal and Kuakata where As concentrations are higher (10 $\mu g \cdot L^{-1}$) in the deepest groundwater (>270 mbgl) than at shallower depths between 100 and 250 mbgl (<2 $\mu g \cdot L^{-1}$).

Figure 8a shows that for stable isotope ratios of oxygen and hydrogen, there is a different regression line for the deeper (>100 mbgl) groundwaters relative to shallow groundwaters (<100 mbgl). The deep sites (Figure 8) give a regression line of $\delta^2H=8.3\delta^{18}O + 10.2$ per mil VSMOW, consistent with the global meteoric water line (Craig, 1961); the slight offset is consistent with colder meteoric temperatures compared to present day. Shallow sites have a regression line of $\delta^2H=6.8\delta^{18}O + 0.82$ per mil VSMOW, either indicative of fractionation processes prior to recharge or of a deviation in the current regional meteoric water line. These data suggest a long-term shift in regional climate and associated meteoric signatures and/or a change in recharge sources or processes. In addition, in some instances the isotope signatures may be used to demonstrate mixing processes and leakage as in the case of the two deep public supply sites in Khulna which are characterised by distinct isotope and % modern recharge signatures. The relevance of these data in identifying recharge sources for deep groundwater will be tested using groundwater flow pathways modelled under different pumping regimes in allied work.[5]

[5] Shamsudduha, M., Zahid, A. and Burgess, W.G. (*in review*) Security of deep groundwater against arsenic ingress in SE Bengal Basin.

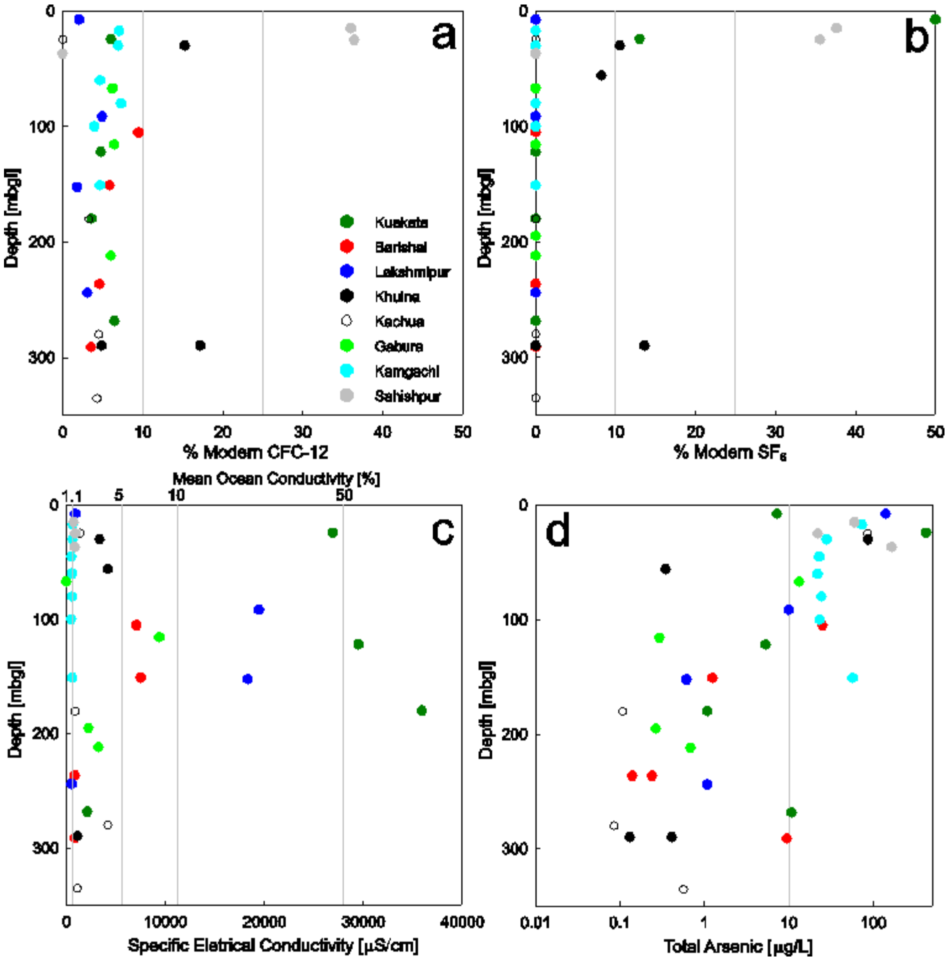

Figure 7. Depth profiles for groundwater residence time tracers a) CFC-12 and b) SF_6, data presented as % modern recharge, c) SEC (μs·cm^{-1}) and d) total dissolved arsenic (μg·L^{-1}), note the log scale for the x-axis. Residence time tracer results have been corrected for temperature and excess air. A binary mixing model, assuming mixing between modern recharge and tracer 'dead' water, has been used to estimate the % modern recharge. Measurement precision is within ±5 % for CFC-12 with a detection limit of 0.05 pmol/L. Measurement precision is within ±10 % for SF_6 with a detection limit of 0.1 fmol/L.

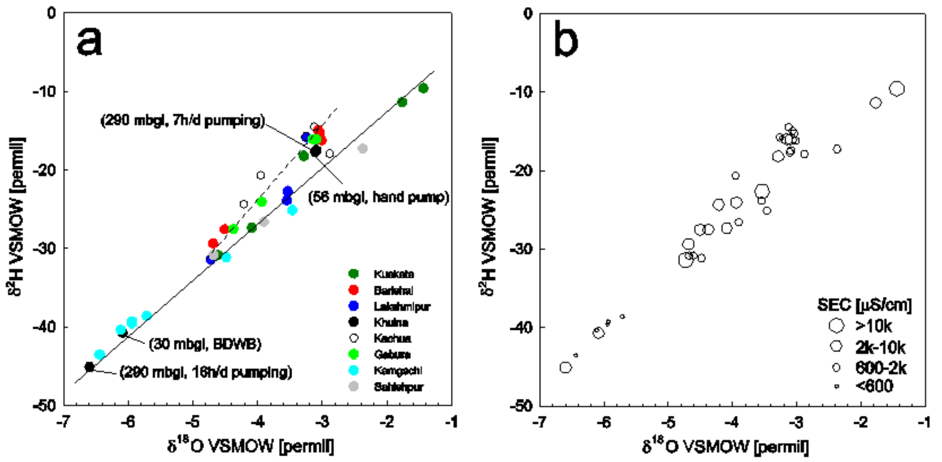

Figure 8. Cross-plot of $\delta^{18}O$ vs $\delta^{2}H$, (a) grouped by site and (b) grouped by SEC (μs·cm^{-1}) categories relevant for drinking water and irrigation standards. Figure 8a has been annotated to illustrate Khulna sites with different depths and pumping regimes. Regression lines for shallow sites (<100 mbgl) shown as a solid line, regression line for deeper sites (>100 mbgl) shown as a dashed line.

4.2 PROJECTED INTENSIFICATION OF RAINFALL IN BANGLADESH

The analysis of General Circulation Model (GCM) projections for the twenty-first century over Bangladesh (Figure 9) suggests an increase in mean rainfall consistent with projected increases in rainfall across the tropics more generally. This result is similar in the analysis of GCMs contributing to the IPCC's AR4 and AR5. At the broader scale, this finding is part of a wider quasi-global rich-get-richer pattern in which regions of moisture convergence (divergence) are expected to experience increased (decreased) rainfall. It is noteworthy that projected changes to extreme (90^{th} percentile) monthly rainfall driving seasonal groundwater recharge are of greater magnitude than changes projected for mean monthly rainfall. Further experiments within the 5° domain (Figure 3) demonstrate that these results (*i.e.* increased rainfall and preferential intensification of extreme rainfall) are robust irrespective of sub-domain location. The projected changes in the higher moments of the rainfall distribution are an important dimension to non-stationarity in future climate and, as shown here, have important implications for groundwater recharge. In areas with suitably permeable surficial sediments, more intensive seasonal rainfall could benefit groundwater recharge if sufficient groundwater storage is made available through dry season abstraction (*i.e.* 'Ganges Water Machine'[6]). On-going research is focussed on recharge processes where sub-daily (hourly) time series records of rainfall and groundwater levels have been collated at two sites of contrasting surface geology in central Bangladesh (Savar, Bhuapur).

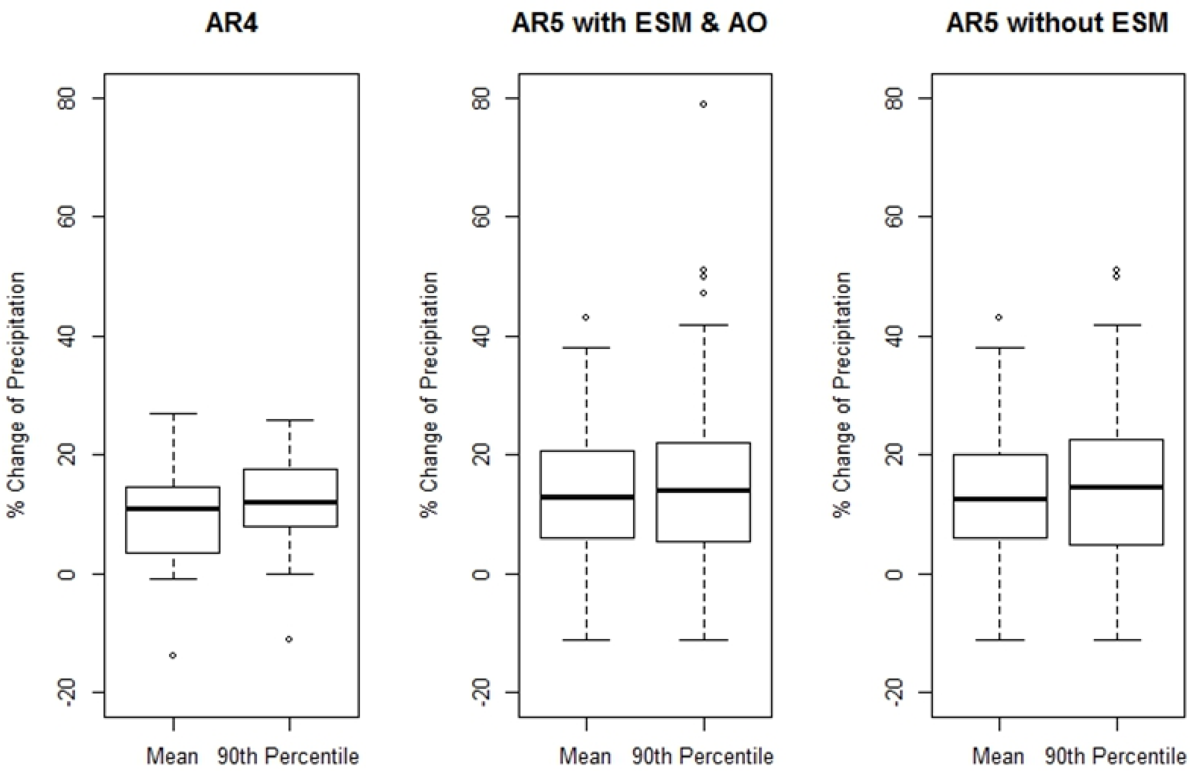

Figure 9. Projected changes in precipitation over the period 2070–2099 relative to 1961–1990 for the 5° box (Figure 3) in Bangladesh from multi-model ensembles of CMIP3 (AR4) under the A1B emissions scenario (23 GCMs) (left), CMIP5 (AR5) under the RCP8.5 scenario (21 GCMs including 8 new ESMs) (middle), and CMIP5 (AR5) under the RCP8.5 scenario (13 GCMs without new ESMs) (right). Tukey box plots are of changes in monthly precipitation for each model in the MME. Dots indicate individual models within the MME sample, boxes show the inter-quartile range and median and circles show the mean of the MME sample.

[6] Revelle, R. and Lakshminarayama, V., 1975. The Ganges Water Machine. *Science* 188: 611-616.

4.3 INTENSIVE ABSTRACTION OF SHALLOW GROUNDWATER FLUSHES ARSENIC

Constructed GRMs (Generalised Regression Models) both nationally and regionally within Holocene deposits reveal inverse associations between observed As concentrations and three covariates[7] (Figure 10): (1) net changes in mean recharge between pre-developed and developed groundwater-fed irrigation periods; (2) hydraulic conductivity of the shallow aquifer; and (3) groundwater-fed irrigation trends (1985−1999). GRMs show further that the spatial variation of As concentrations is well explained by not only surface geology but also statistical interactions (*i.e.* combined effects) between surface geology and mean groundwater recharge, thickness of surficial silt and clay, and well depth. Collectively, these associations are consistent with the assertion that irrigation-induced recharge serves to flush mobile As from shallow groundwater. Our results suggest that shallow groundwater-fed irrigation redistributes As to the soil where it can continue to pose a threat to human health and food security.

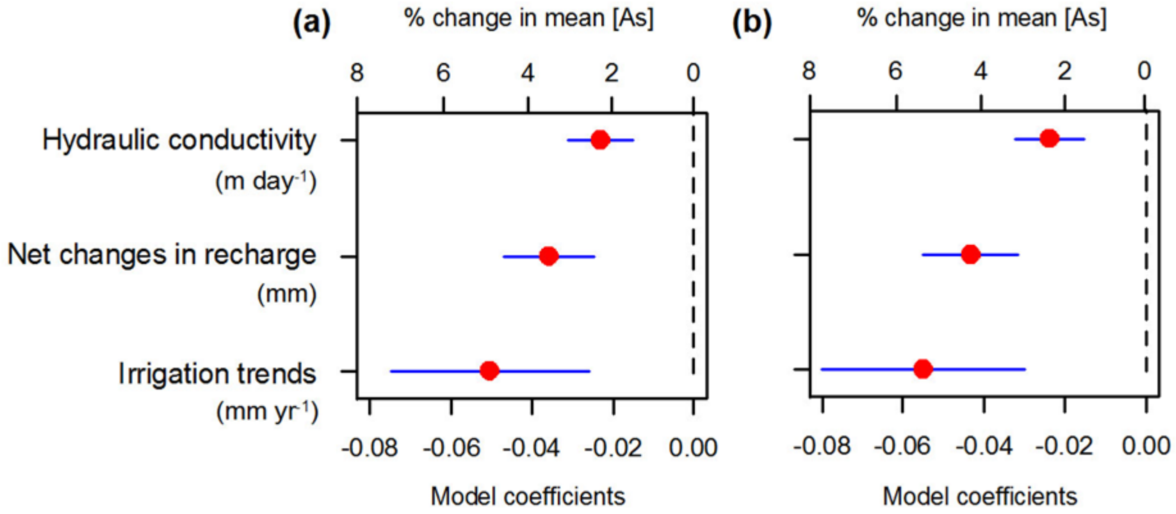

Figure 10. Graphical summary of the key GRM results from (a) national and (b) regional scale analyses[6]. Model coefficients of three important covariates with their error bars (± standard error) are shown in the bottom axis. The top axis shows equivalent change (in percentage) in mean As concentrations with an 1-unit increase of these covariates.

[7] Shamsudduha, M., Taylor, R.G., and Chandler, R., 2015. A generalised regression model of arsenic variations in the shallow groundwater of Bangladesh. *Water Resources Research* 51: 685-703.

5 Concluding remarks – emerging questions & links to policy: The Bengal Deep Groundwater Statement 2014

The *Deep groundwater in the Bengal Mega-Delta: new evidence of aquifer hydraulics and the influence of intensive abstraction* case study has generated evidence which is enabling a greater understanding of BAS at the depths where abstraction is rapidly accelerating, of the relationship between the deep and shallow parts of the aquifer system, and the likely impact of climate change on rainfall intensity. This new evidence will enable more robust evaluation of the response of deep groundwater in the GBM delta region to increasing development and to climate change. Discrete and original observations have been made of groundwater head and groundwater chemistry including environmental isotopes and age indicators in vertical profiles to a maximum depth of 320 m at eight locations in the southern and coastal region of the delta region. A new assessment has been made of changes in rainfall intensity that may be expected as a result of climate change towards the end of the 21st century. Considered together, and in the light of allied research, the headline conclusions are:

• Temporal variations in deep groundwater levels, remote from intensive abstraction, are dominated by the elastic responses of the aquifer sediments to surface loading associated with tidal water bodies and monsoonal flooding. These annual changes in terrestrial water storage are largely independent of groundwater flow.

• Changes in the sources of recharge to deep groundwater in response to prolonged intensive groundwater abstraction pumping are suggested by chemical tracers (CFC-12, SF_6, stable isotope ratios of O and H) and new high-resolution piezometric observations.

• The volume and intensity of rainfall is projected to increase as a result of climate change in the Bengal Mega-Delta with a potential benefit to groundwater recharge where storage can be made available through intensive shallow groundwater abstraction for dry season irrigation of boro rice. Induced groundwater recharge serves, however, to flush mobile As, redistributing it to the soil.

Clear guidance for policy makers has been made in relation to the deep groundwater resource of the GBM delta region: *The Bengal Deep Groundwater Statement 2014* (below). Nevertheless, critical questions remain to be addressed in support of the resource management and further policy development:

- To complement the findings of this study, the extent and discontinuity in fine sediment layers confining deep groundwater in BAS and variation in their effective vertical permeability need to be further established.
- Despite much progress (*e.g.* Figure 4), further work is necessary on the spatial extent and vertical layering of groundwater salinity in the delta region.
- For the continuing and expanded development of deep groundwater as a secure source of water, the implementation and strengthening of robust structures and infrastructure for monitoring and management are an essential requirement.
- Broader hydrological questions remain in relation to water distribution and storage throughout the IGB basin, the impacts of changes in climate on the hydrology of the GBM delta region, and especially in the context of this study the impacts on surface water storage and recharge to the BAS.

5.1 THE BENGAL DEEP GROUNDWATER STATEMENT 2014: DEEP GROUNDWATER IN BANGLADESH: A VITAL SOURCE OF WATER

This Statement is the consensus outcome of collaboration between groundwater scientists and engineers working in academia (Dhaka University, Bangladesh University of Engineering & Technology, University College London, IIT Kharagpur) and Government survey / monitoring departments (Bangladesh Water Development Board, British Geological Survey), in discussion with planners in Bangladesh Government agencies (PSU, WARPO) and international bodies (UNICEF).

Deep groundwater is a vital resource for public water supply and irrigation in Bangladesh. The aim of ***The Bengal Deep Groundwater Statement 2014*** is to provide a status update for the benefit of those with responsibility for water supply in Bangladesh, particularly for policy makers.

The Statement summarises the consensus reached at a Seminar[8] and Workshop[9] attended by key representatives of the Policy Support Unit (PSU, Local Government Division, Ministry of LGRD & Cooperatives), the Water Resources Policy Organisation (WARPO), the Bangladesh Water Development Board (BWDB), the Geological Survey of Bangladesh (GSB), the Bangladesh Agricultural Development Corporation (BADC), donors including UNICEF, national and international universities and NGOs. Evidence and experiences of deep groundwater conditions in Bangladesh and West Bengal, including new research results, were considered and their implications for policy were discussed.

The Statement identifies 7 points of consensus (A to G below) drawn from new research[10] on deep groundwater conditions in the Bengal Basin. To facilitate contribution to the aims of the Bangladesh 'Water Act'[11], these points subsume conclusions and recommendations taken from the 2013 Ruposhi Bangla Deep Groundwater Statement[12], integrating new findings with observations, field investigations and modelling results subsequent to the first substantive discussion on deep groundwater[13] in 2000, when few facts were available.

The 'Water Act' drives the requirement for policy development, but this Statement also recognises the context jointly provided by the UNEP IHP Trans Boundary Waters Assessment Programme (WAP) No. 16 for Central Asia[14], media and other reports of groundwater depletion across parts

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[8] 'Resilience of Deep Groundwater in the Delta Region of Indo-Gangetic Basin', convened by Professor Richard Taylor (University College London) and Prof. Kazi Matin Ahmed (Dhaka University), 26th Nov. 2014, Dhaka.

[9] 'Groundwater monitoring in the Bengal Basin: identifying research strategies and their policy implications', convened by Dr. William Burgess (University College London), Professor Kazi Matin Ahmed (Dhaka University) and Mr. Kazi Abdul Noor (Policy Support Unit, Local Government Division, Ministry of LGRD & Cooperatives), 27th Nov. 2014, Dhaka.

[10] The case study 'Deep groundwater in the Bengal Mega-Delta: new evidence of aquifer hydraulics and the influence of intensive abstraction' was funded by UKAid under the programme 'Groundwater resources in the Indo-Gangetic Basin: resilience to climate change and pumping', managed by the British Geological Survey (BGS). Access to piezometers at six sites across coastal Bangladesh, and contextual data, were provided by the Bangladesh Water Development Board (BWDB).

[11] 'The Coordinated Development, Management, Extraction, Distribution, Use, Protection and Preservation of Water Resource' (Bangladesh National Parliament, 2 May 2013). Objectives under the Water Act require guidance on safe yield and sustainable limits of water resource bodies.

[12] Policy Note submitted to PSU, 2013. Available as Appendix H of the Report 'The Security of Deep Groundwater in Bangladesh: Recommendations for policy to safeguard against arsenic and salinity invasion' (UCL, 2013).

[13] 'Deeper Aquifers of Bangladesh – A Review Meeting", (DPHE/UNICEF/WB 2000). Organised by DPHE with support from UNICEF and WSP-SA, World Bank, and the LGD, Ministry of LGRD and Co-operatives, Government of the People's Republic of Bangladesh. The meeting addressed the prospects for a postulated 'deep aquifer'. Over ensuing years the concept 'deep groundwater' has become preferred to 'deep aquifer', as hydraulic continuity within the 'Bengal Aquifer System' is now recognised at regional and whole-basin scales – see Point A.

[14] http://www.geftwap.org/; http://www.unwater.org/downloads/UNW_TRANSBOUNDARY.pdf

of the Indo-Gangetic plains[15], the water-food-health nexus[16] with its requirement for adaptive strategies to strengthen resilience in the face of climate change, and many cases across Bangladesh[17] of urban and mega-city reliance on groundwater for water supply where the sustainability of the groundwater resource is uncertain or under threat.

Deep groundwater pumping has become the most popular, practical and economic mitigation[18] response to the arsenic crisis, with many tens of thousands of deep tubewells installed for hand-pumped domestic supplies, rural piped systems, and municipal and commercial supplies. High-yielding deep wells have been installed in over 100 rural water supply schemes and at more than 20 towns. At some sites, researchers have made detailed studies of deep groundwater. Also a number of modelling studies have been performed. Against a backdrop of concern for the sustainability of deep groundwater resources, and their security against invasion by arsenic and in coastal regions, salinity, there has to date been no adverse impact on quality or water levels that can be attributed to deep groundwater pumping, except in Dhaka. [In the Dhaka metropolitan area, groundwater levels continue to decline as the number of deep boreholes increases; no-where else in southern Bangladesh is the water demand as large and as concentrated as in Dhaka]. There is still much to learn, but the stage has been reached when clear conclusions pertaining to the managed development of the deep groundwater resource, with concurrent monitoring of quality and water levels, are justified.

We emphasise the following conclusions and recommendations as advice to policy makers[19]:

A. Deep groundwater defined

The subject of the Statement is 'deep groundwater'. We take 'deep groundwater' to be groundwater at greater than 150 m depth below the ground surface of the Ganges-Brahmaputra-Meghna (GBM) floodplains of the Bengal Basin, irrespective of its age and the age or nature of its host sediments. We emphasise that the sediments of the Bengal Basin have a common geological origin and form one single, inter-connected aquifer, the Bengal Aquifer System (BAS)[20], which stores and transmits groundwater over time in an interconnected fashion. The deep groundwater resource remains poorly defined, however, and the spatial variability of BAS is not well characterised. Interconnectedness dictates that pumping from one level may have impact beyond, above and/or below the point of pumping. Over short times (weeks, months) these impacts may not be significant. Locally, identifiable sub-division of BAS into discrete aquifers might be useful.

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[15] Rodell et al., 2009. *Nature* 460, pp. 999-1002; Tiwari et al., 2009. *Geophysical Research Letters* 36, L18401; Shamsudduha et al., 2012. *Water Resources Research* 48, W02508.

[16] World Economic Forum (WEF), 2011. Water Security: The Water-Food-Energy-Climate Nexus. 2011. WEF Initiative, Washington, DC: Island Press; BRAC, 2013. Sustainability of Groundwater Use for Irrigation in Northwest Bangladesh. Report to the National Food Policy Capacity Strengthening Programme (NFPCSP).

[17] UCL (2013). The security of deep groundwater in southeast Bangladesh: recommendations for policy to safeguared against arsenic and salinity invasion. Final Report, EPSRC/UCL-BEAMS Knowledge Transfer Project, London. 78 pp; Burgess, W.G., Hasan, M.K., Rihani, E., Ahmed, K.M., Hoque, M.A. and Darling, W.G. (2011) Groundwater quality trends in the Dupi Tila aquifer of Dhaka, Bangladesh: sources of contamination evaluated using modelling and environmental isotopes, International Journal of Urban Sustainable Development (3), 56–76.

[18] Deep tubewells account for 70% of the mitigation response to the arsenic crisis, across Bangladesh (DPHE/JICA, 2009. Situation Analysis of Arsenic Mitigation. Local Government Division Bangladesh, Department of Public Health Engineering (DPHE), and Japan International Cooperation Agency (JICA) Bangladesh, Dhaka, pp. 77).

[19] These points follow from research reported in 'The Security of Deep Groundwater in Bangladesh: Recommendations for policy to safeguard against arsenic and salinity invasion' (UCL, 2013), and broader discussions during the Seminar and Workshop of 15/16th January 2013.

[20] Michael, H.A. and Voss, C.I. (2009) Controls on groundwater flow in the Bengal Basin of India and Bangladesh: regional modeling analysis. *Hydrogeology Journal* 17 (7), 1561-1577. Burgess, W. G., Hoque, M. A., Michael, H. A., Voss, C. I., Breit, G. N., Ahmed, K. M. (2010). Vulnerability of deep groundwater in the Bengal Aquifer System to contamination by arsenic. *Nature Geoscience* 3(2), 83-87.

However over long time periods (years, decades) and at large scales it should be expected that the effects of pumping will be widely experienced. Therefore:

i) we recognise ‘deep groundwater’ rather than ‘the deep aquifer’;

ii) we note that there is a need to delineate more fully the quantity and extent of deep groundwater resources;

iii) we emphasise the imperative to monitor the effects of deep groundwater pumping across the full depth sequence of BAS sediments;

iv) we note that the BAS is a transboundary aquifer, crossed by an international boundary;

v) we stress the value of a co-operative approach to groundwater resource management, and the wider benefits of knowledge sharing.

B. Strategic importance of deep groundwater for water supply, health and development

There is consensus between the institutions and individuals with concern and responsibility for water supply in Bangladesh in recognising the significance of deep groundwater to the future of Bangladesh. The consequences of not developing deep groundwater would be: less-secure water sources would be targeted; arsenic exposure of the rural population would decline less than otherwise or not at all; and the potential for development offered by a safe, secure water supply would not be realised.

C. Threats to sustained good quality of deep groundwater

Whereas at shallow depth across the GBM floodplains, arsenic is a pervasive groundwater contaminant, and in many coastal areas groundwater at shallow and/or intermediate depth is saline, the quality of deep groundwater is generally very good. It is recognised that heavy pumping of deep groundwater may induce the downward migration of arsenic in many parts of Bangladesh, and of salinity in coastal regions[19]. Sea-level rise, amplification of storm surges and intensification of rainfall that result from climate change may exacerbate threats to the quality of deep groundwater. There is, nevertheless, consensus that:

i) Excessive abstraction poses a greater threat to the quality of deep groundwater than does climate change.

ii) Changes in groundwater quality will be gradual, and monitoring should provide adequate warning of adverse effects, giving time for a managed response.

D. Equitable access requires strong regulation

Intensive pumping of shallow groundwater has in some areas, and particularly where fine-grained soils restrict replenishment by monsoonal recharge, led the water table to fall[21], restricting groundwater access to those able to afford deeper wells and increasing dependence upon deep groundwater resources. We draw attention to the inequity in access that results from unregulated pumping of groundwater, and we recommend strong regulation of deep groundwater pumping as a pro-poor policy.

E. Monitoring deep groundwater – *you cannot manage what you do not monitor*

Shallow groundwater in Bangladesh is one of the most intensively monitored groundwater regimes in the world; the monitoring database developed by BWDB has generated valuable insights of the sustainability of shallow domestic and irrigation pumping and the vulnerability of the shallow groundwater resources to contamination. In contrast, deep groundwater remains largely

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[21] Shamsudduha, M., Chandler, R. E., Taylor, R. G., & Ahmed, K. M., 2009. Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna Delta. *Hydrology and Earth System Sciences*, 13: 2373-2385.

unmonitored[22], despite its strategic importance (point B). We emphasise that '*you cannot manage what you do not monitor*'. Recent, localised and high-frequency monitoring of deep groundwater pressure and chemistry has shown that BAS is susceptible to a variety of influences[23] that are still not fully understood. We recommend:

i) continued exploration and testing of deep groundwater conditions and the hydraulic character of BAS at depths between 150 and 350 m;

ii) implementation of a coordinated, national-scale, purpose-designed 'deep groundwater monitoring programme' combining both groundwater level and groundwater quality.

F. Groundwater and adaptation – increasing seasonal water capture and storage

Substantial increases in demand for water for domestic purposes, irrigation and industry are anticipated in coming decades. The intensification of rainfall projected for Bangladesh as a result of climate change (see point C above) is expected to amplify seasonality in availability of water resources of Bangladesh. Successful adaptation strategies are likely to require improved capture and storage of monsoonal flows to enhance the sustainability of shallow groundwater use and in doing so to reduce dependence upon deep groundwater resources. We recommend adaptation strategies that increase seasonal water capture through:

i) expansion of schemes for the creation of shallow freshwater lenses through Managed Aquifer Recharge (MAR)[24];

ii) consideration of MAR more widely in areas underlain by permeable soils, where monsoonal replenishment of groundwater abstracted for dry-season irrigation may be possible.

G. Groundwater governance

Currently in Bangladesh, multiple agencies are involved in the governance and development of groundwater resources (BWDB, WARPO, PSU, DPHE, BADC, DWASA, KWASA, others?). There remain barriers to the sharing of data and communication of knowledge between research institutions, water supply providers, and agencies of governance. We recommend:

i) implementation of the Water Act through a single agency, with a clearly defined structure for devolved responsibilities;

ii) strong inter-ministerial coordination and a dedicated framework (e.g. Task Force) to streamline data storage and access at national level;

iii) capacity strengthening, with particular attention to disciplines including groundwater hydrology, earth sciences and environmental engineering, to underpin the needs of groundwater resources evaluation, monitoring and governance.

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[22] The notable exception is the BWDB network of 39 nested piezometer sites across the coastal area of Bangladesh monitored throughout 2012-2013 under the 'Climate Change Trust Fund (CCTF) of the Ministry of Environment. We applaud the vision of this monitoring programme, and encourage its continuation and extension.

[23] Burgess et al., 2014. *Poster H51O-0819*. AGU Fall Meeting, San Francisco 15-19 December 2014.

[24] Managed aquifer recharge experiments focussing on shallow groundwater are delivering positive results at locations in south-west coastal regions (Sultana, S., Ahmed, K., Mahtab-Ul-Alam, S., Hasan, M., Tuinhof, A., Ghosh, S., Rahman, M., Ravenscroft, P., and Zheng, Y. (2015). "Low-Cost Aquifer Storage and Recovery: Implications for Improving Drinking Water Access for Rural Communities in Coastal Bangladesh." *J. Hydrol. Eng.* 20, SPECIAL ISSUE: 8th International Symposium on Managed Aquifer Recharge, B5014007.)