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ORIGINAL ARTICLE

Security of deep groundwater against arsenic contamination in the Bengal Aquifer System: a numerical modeling study in southeast Bangladesh

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Abstract

Across the floodplains of southern Bangladesh deep (> 150 m belowground level, bgl) groundwater within the Bengal Aquifer System (BAS) has become widely used for domestic water supply as a de facto mitigation response to the presence of excessive arsenic (As), exceeding the World Health Organization standard of 10 μg L^{-1}, in shallow groundwater. Over the past 10 years, many hand-pumped tube wells and high-capacity municipal water-supply wells have been installed at this depth and at deeper regions of the BAS, which are almost uniformly free of excessive As. Concern for the security of the deep groundwater resource against possible invasion of As and saline water from shallow depths emphasizes the need for comparative assessments of groundwater abstraction strategies to guide water resource managers and policy makers. To this end, particle-tracking post-processing has been applied within a numerical groundwater flow model for an area of over 10,000 km^2 in southeastern Bangladesh, one of the regions where the As issue is most acute. Criteria for describing the security of deep groundwater abstraction strategies over a 100-year time frame have been applied to the model outcomes for a range of scenarios. Our analyses suggest that deep groundwater will remain secure against invasion of As across the entire region if it is restricted to domestic use, even under domestic demand projected for 2050. Our approach can be applied in other regions and in similar Asian mega-deltas where As contamination of groundwater is recognized as a grave concern for sustainable water resources development.

Keywords Water supply · Vulnerability · Groundwater modeling · Particle tracking · Bangladesh

Introduction

The extensive and excessive occurrence of arsenic (As) in groundwater of the Bengal Aquifer System (BAS) in Bangladesh (Fendorf et al. 2010), mostly within 100 m of the ground surface across the floodplains of the Ganges, Brahmaputra and Meghna Rivers, is resulting in a national public health catastrophe (Ravenscroft et al. 2009; Smith et al. 2000). Groundwater from shallow hand-pumped tube wells (HTWs) installed at a few tens of meters to 150 m belowground level (bgl) is used for domestic supply by 80% of the population (BGS and DPHE 2001; Rahman and Ravenscroft 2003). Most of these tube wells are privately owned and are operated throughout the year at a very low discharge rate, < 1 L s^{-1} (Ali 2003); approximately, 27% provide water exceeding the Bangladesh national limit of As in drinking water (50 μg L^{-1}), and 46% exceed the World Health Organization guideline value (10 μg L^{-1}). Deeper groundwater throughout Bangladesh (> 150 m bgl) is almost uniformly free of excessive As (Burgess et al. 2010) and therefore installation of deep wells for domestic water supply has become a popular, practical and economic mitigation response to the As crisis (Ravenscroft et al. 2013). By 2005, a total of 150,000 deep hand-pumped tube wells (> 150 m bgl) had been installed throughout Bangladesh (Ravenscroft

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et al. 2009), of which more than 20,000 are located within southeast Bangladesh, the focus of interest for the present study (UCL 2013). In addition, deep wells with high-capacity pumps (> 20 L s^{-1}) have been installed at depth of > 150 m bgl by the Bangladesh Department for Public Health Engineering (DPHE) in over 100 rural water supply schemes and in more than 20 municipal schemes (UCL 2013). Recent studies have demonstrated through observations and numerical modeling that long-term, intensive municipal pumping of deep groundwater in Dhaka City is threatening groundwater quality in previously As-safe shallow (30–90 m bgl) and intermediate (90–150 m bgl) zones at over 20 km from the city limits (Knappett et al. 2016). The potential vulnerability of deep wells to contamination by As drawn down over time from shallow levels (Burgess et al. 2010) is therefore of critical importance to the security of sustainable water supply in Bangladesh (Ravenscroft et al. 2013). Contamination by salinity in some areas is also an acknowledged, but unquantified, risk (Burgess et al. 2010). Saline groundwater occurs at shallow to intermediate depths across much of the coastal region in Bangladesh (DPHE/DANIDA 2001; Ravenscroft and McArthur 2004). Intensive pumping from deep groundwater may ultimately induce invasion of saline groundwater even before As-rich groundwater can travel to the abstraction point of deep wells (Burgess et al. 2010).

Groundwater-fed irrigation of rice takes place during the dry season (December–April) throughout rural Bangladesh, with the total volume of groundwater pumped for agricultural purposes being an order of magnitude greater than that total pumped for domestic use (Michael and Voss 2009a). In 2006, approximately 78% of irrigated rice fields in Bangladesh were supplied by groundwater, of which approximately 80% was derived from low-capacity irrigation tube wells (about 1.2 million wells pumping from shallow depth, mostly at 25–50 m bgl, capacity 10 L s^{-1}), and the remainder from high-capacity tube wells (about 29,000 wells pumping from depth 75–100 m bgl, capacity 56 L s^{-1}) installed by government agencies such as the Bangladesh Agricultural Development Corporation (BADC) and the Barind Multipurpose Development Authority (BMDA) (BADC 2008; Shamsudduha et al. 2011). Irrigation tube wells at these intermediate depths (75–100 m bgl) are also ultimately vulnerable to As invasion from shallow depths (< 50 m bgl) (Cuthbert et al. 2002), and, in places, to invasion of salinity (Lapworth et al. 2018). Hence, there are pressures for irrigation water to be derived from deeper wells as a safeguard against contamination of rice crops and the potential adverse impacts on agricultural yields (Ravenscroft et al. 2009).

The geological development of the Bengal Aquifer System (BAS) since the Plio-Quaternary time has been summarized in Burgess et al. (2010). The BAS stratigraphy (Fig. 1) comprises a succession of Quaternary fluvial and deltaic sediments overlying a Mio-Pliocene shale of basin-wide extent at 1–2 km depth, which provides a hydraulic basement to the aquifer system. Glacioeustatic fluctuations in sea level over the Quaternary time led to thick sequences of fine to coarse sands intercalated with discontinuous lenses of silty-clay and paleosol layers of low permeability, which resulted in a horizontal–vertical anisotropy in hydraulic conductivity at the regional scale in the order of 10^4 (Hoque et al. 2017; Michael and Voss 2009b). Although there is likely hydraulic connection throughout the BAS at basin scale and to depths of several hundreds of meters over long time periods, discrete aquifer and aquitard layers have been recognized in places. A silt–clay aquitard commonly present at shallow depth beneath the Holocene floodplains (MMI 1992; Ravenscroft and McArthur 2004) locally separates an unconfined aquifer from deeper, confined groundwater, as in West Bengal (McArthur et al. 2008; Mukherjee et al.

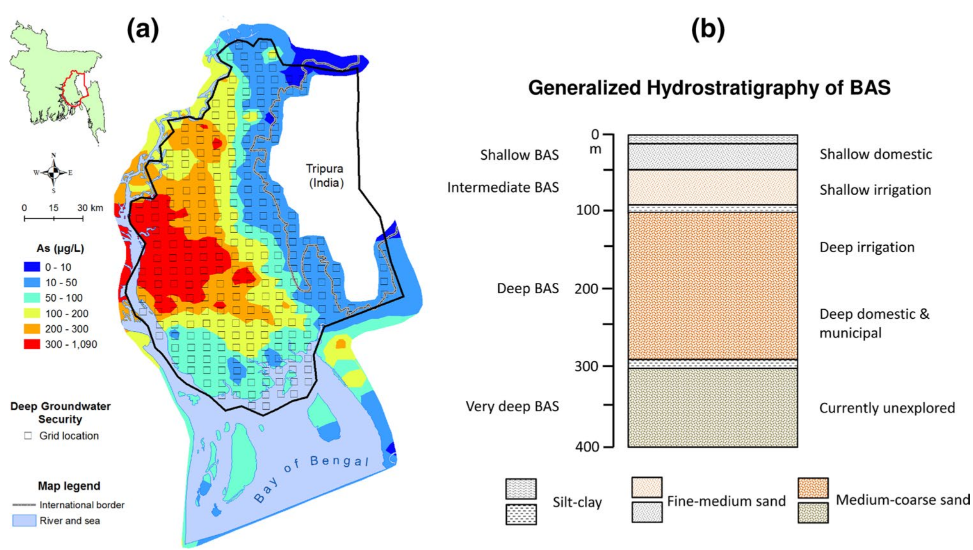

Fig. 1 **a** Study region, showing the distribution of the excessive As (< 50 µg L^{-1}) in shallow groundwater derived from the National Hydrochemical Survey of Bangladesh (BGS and DPHE 2001; DPHE 1999); the map also shows the groundwater model domain and the distribution of an array of grids used in mapping deep (200 m bgl) groundwater security (grids within Tripura (India) are not shown on the map, but are included in the analyses); **b** a generalized hydrostratigraphy of southeastern BAS (modified after Zahid et al. 2015) with reference to current groundwater abstraction strategies

2007), at Khulna (population ~ 1 million) in southwestern Bangladesh (LGED/BRGM 2005), and in western Bangladesh (Burgess et al. 2007). At Khulna, deep groundwater pumping has been maintained for over 30 years for municipal supply, unaffected by As or salinity breakthrough from shallower levels (LGED/BRGM 2005). These observations and experiences taken together have led to suggestions that the 'deep aquifer' (DPHE/UNICEF/WB 2000; Ravenscroft et al. 2009) might be more widely developed, but there is concern that deep groundwater may be vulnerable to As invasion as a consequence of pumping (Burgess et al. 2007; DPHE/DFID/JICA 2006).

To address the issue of deep groundwater vulnerability at the scale of the whole basin, Michael and Voss (2009a, b) developed a groundwater flow model representing the Bengal Aquifer System as a single aquifer with homogeneous, anisotropic hydraulic conductivity (K_h/K_v value of 10^4) and imposing groundwater pumping evenly across the region. They concluded (Michael and Voss 2008) that deep groundwater "could provide arsenic-safe drinking water to > 90% of the arsenic-impacted region over a 1000-year timescale … if its utilization is limited to domestic supply". A further study (Radloff et al. 2011) uses solute transport modeling within the groundwater flow field of the basin-scale model to suggest that As migration to depths greater than 150 m bgl may take > 1000 years depending on the magnitude of adsorption of As to aquifer sediments. On account of their homogeneity, these basin-scale models are not representative at specific locations where lithological heterogeneity might locally allow more rapid penetration of As to deep groundwater (Burgess et al. 2010; Hoque et al. 2017; Michael and Voss 2008); also, they do not include the spatially focused effects of high-capacity pumping for municipal water supply (Radloff et al. 2011). Application of a 1000-year time frame as a criterion for sustainability has also been challenged, along with the concept of sustainable groundwater abstraction in this context (Ravenscroft et al. 2013). This challenge advocates a 'weak sustainability' approach (Ayres et al. 2001) and stresses the ethical value of time-limited groundwater abstraction at rates that are ultimately unsustainable (Price 2002). Empirical re-appraisal of 46 deep wells in south-central Bangladesh by Ravenscroft et al. (2013) shows groundwater composition at > 150 m depth having remained unchanged for the 13 years between 1998 and 2011 and with no deterioration inferred over the operating lifetimes of the deep tube wells concerned, between 20 and 43 years.

Common to both basin-scale modeling and empirical repeat sampling are questions concerning hydrogeological variability, the impact of distributed high-capacity pumping for municipal water supplies and irrigation, and the required duration of deep groundwater security as a basis for policy choices and decision making. These issues are addressed in the methodology and application of models described below.

Approach and methodology

Here, we employ a groundwater flow model of southeast Bangladesh (Fig. 1) which (a) distributes deep groundwater pumping according to population density across the region by upazila (the third administrative level in Bangladesh), and (b) represents lithological variability in the aquifer system using a six-layered hydrostratigraphy with spatially uniform, vertically anisotropic hydraulic conductivity fields. Partial discontinuity of the aquitards across the model region, indicated by vertical profiles of groundwater head (Zahid 2008; Zahid et al. 2015) and synthesis of lithological profiles (Burgess et al. 2010; Hoque 2010; Hoque et al. 2017), has additionally been incorporated. Groundwater abstractions in the model are distributed spatially and with depth in representation of two pumping strategies of particular interest to water resource managers and policy makers: one (the current strategy) in which pumping is distributed with depth according to its purpose and the other (a consideration for the future) in which all pumping is focused within a depth range 200–250 m bgl. Groundwater abstraction rates across the study region have been quantified for one recent time (2004) and estimated for one future time (2050).

We have applied the results to evaluate the security of the groundwater resource over a limited time period, rather than sustainability of the groundwater abstractions, acknowledging in common with Ravenscroft et al. (2013) that strategically valuable solutions providing a safe water supply lasting decades or longer are of legitimate interest to planners despite being time limited and ultimately unsustainable. We use a 100-year time period for comparison of the security of the deep groundwater resource under alternative pumping strategies, following discussions (UCL 2013) with the Bangladesh Water Development Board (BWDB), Policy Support Unit (PSU), Department of Public Health Engineering (DPHE), Bangladesh Agricultural Development Corporation (BADC), Bangladesh Rural Advancement Committee (BRAC) and UNICEF in Bangladesh. Secure solutions over a 100-year term are accepted to be of strategic value, even though the proposed groundwater abstractions may ultimately be unsustainable in the very long (e.g., 1000-year) term. Applying the evaluations at multiple points in a regular grid across the region leads to maps of deep groundwater security, which underpin recommendations to policy makers on the potential role of deep groundwater as a long-term source for water supply in southeastern Bangladesh. An equivalent analysis is presented with respect to groundwater salinity, variously present at up to 100 m depths and posing an additional threat to the quality of groundwater pumped from greater depths in the coastal regions of the BAS.

Choice of groundwater flow model

We apply numerical groundwater flow models developed by Zahid et al. (2015) to depths of approximately 2500 m in southeastern Bangladesh. A set of steady-state, three-dimensional groundwater flow models was constructed using the United States Geological Survey MODFLOW code (Harbaugh et al. 2000) in the ArgusONE (ArgusONE 1997) open numeric environment, applying MODFLOW-GUI version 4 (Winston 2000). The MODFLOW post-processor MODPATH (Pollock 1994) is used for tracing groundwater flow paths. The primary objective is to apply a simple and effective groundwater flow model representative of the main features in the Bengal Aquifer System, particularly focusing on the deeper part of the flow system. Model hydrogeological features are summarized in Table 1, and full details of model construction can be found in Zahid (2008) and Zahid et al. (2015). A brief description of the model development including hydrogeological parameters, model boundary conditions, calibration and sources of uncertainty is provided below.

Model development

The Bengal Aquifer System (BAS) of Bangladesh and West Bengal (India) is best described as a single groundwater system that comprises a number of regional aquifers which are hydraulically connected on the basin scale (Burgess et al. 2010). Although at a local scale (hundreds of meters to tens of kilometers), distinctive bodies of aquifer and aquitard can be traced from drilled lithological records, these units are not laterally continuous. Michael and Voss (2009a); (2009b) find no evidence for the presence of basin-wide aquitards and thus conceptualize a single uniform, anisotropic aquifer with a high horizontal–vertical anisotropy ($K_h >> K_v$) in which topography drives groundwater flow from the basin margins toward the major rivers and also toward the Bay of Bengal in the south. To incorporate evidence for heterogeneity at a regional scale, as well as depth-distributed pumping (Fig. 2), in the present study of southeast Bangladesh, the model is discretized into a six-layered hydrostratigraphy (Table 1): three discrete 'aquifer' units (aquifer unit 1: 15–75 m, aquifer unit 2: 100–285 m, and aquifer unit 3: 300–400 m) and three 'aquitard' units (aquitard unit 1: 0–15 m, aquitard unit 2: 75–100 m, and aquitard unit 3: 285–300 m) located above a shale- and siltstone-dominated geological unit called the Boka Bil Formation, taken as the hydraulic basement across the region as in the basin-scale model developed by Michael and Voss (2009a). The term 'aquifer' here is used indicatively to distinguish the model layers with greater hydraulic conductivity (range: 1.0×10^{-3} to 1.0×10^{-5} m s^{-1}) from the low-permeable 'aquitard' units (range: 1.0×10^{-5} to 1.0×10^{-7} m s^{-1}). Spatially uniform values of equivalent hydraulic conductivity were assigned to each model layer on the basis of previous hydrogeological investigations (BWDB 1989, 1994; UNDP 1982) and analysis of a number of deep (maximum depth range: 265–326 m bgl) boreholes and geophysical logs in the region (Zahid 2008; Zahid et al. 2015). The common presence of laterally discontinuous layers of silts and silty clays of low permeability within the aquifer layers was accounted for by applying a horizontal–vertical anisotropy in hydraulic conductivity (K_h/K_v) as summarized in Table 1.

A steady-state hydraulic head is applied as a boundary condition at the top of the model, set equivalent to the topographic elevation derived from the Shuttle Radar Topography Mission (SRTM) elevation data. The implication is that hydraulic head cannot be drawn down at the model surface due to pumping, taking into account (together with Michael and Voss 2008) that plentiful and extensive surface water bodies interact freely with the aquifer and potentially provide an unlimited source of water to the aquifer system. The model area (Fig. 1) is bounded by the Meghna River in the west, the Tripura hills in the east, the Titas River in the

Table 1 A summary of groundwater flow model parameters and hydrogeological features (Zahid et al. 2015)

Hydrostratigraphy/ model geological units	Model layer	Horizontal hydraulic conductivity (K_h) (m s^{-1})	Vertical hydraulic conductivity (K_v) (m s^{-1})	Depth (m bgl)
Surficial aquitard	Unit 1	1.0×10^{-6}	1.0×10^{-7}	0–1
Upper aquitard	Unit 2	1.0×10^{-6}	1.0×10^{-7}	1–16
First aquifer (upper)	Unit 3	1.0×10^{-4}	1.0×10^{-5}	16–46
First aquifer (lower)	Unit 4	1.0×10^{-3}	1.0×10^{-4}	46–76
Shallow aquitard	Unit 5	1.0×10^{-6}	1.0×10^{-7}	76–101
Second aquifer (upper)	Unit 6	1.0×10^{-4}	1.0×10^{-5}	101–176
Second aquifer (lower)	Unit 7	1.0×10^{-3}	1.0×10^{-4}	176–286
Deep aquitard	Unit 8	1.0×10^{-6}	1.0×10^{-7}	286–300
Third aquifer (upper)	Unit 9	1.0×10^{-4}	1.0×10^{-5}	300–400
Third aquifer (lower)	Unit 10	1.0×10^{-3}	1.0×10^{-4}	> 400

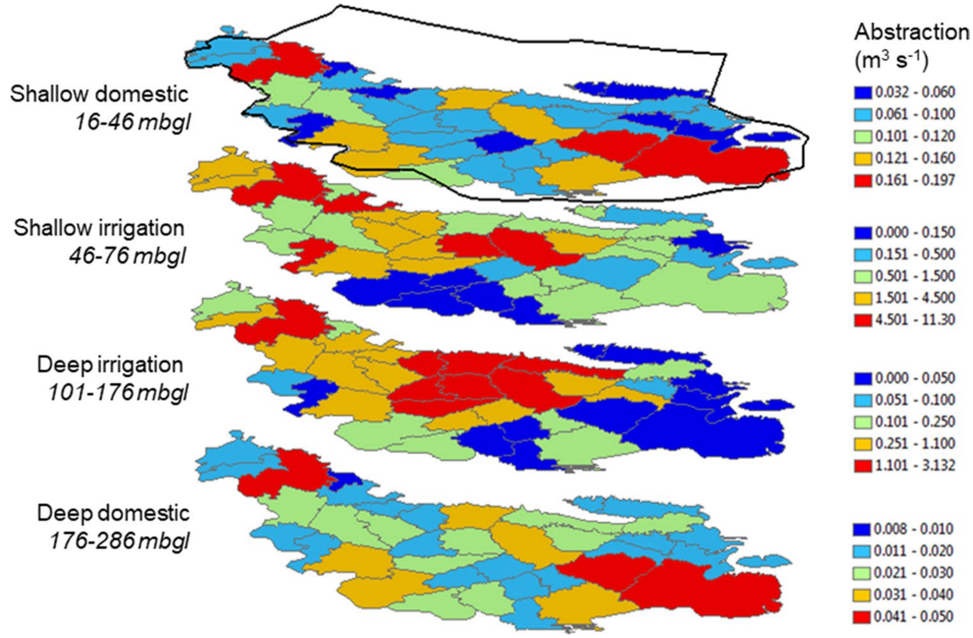

Fig. 2 The spatial distribution of groundwater abstraction for domestic supply and irrigation for the 2003–2004 dry season, illustrated the depth-dependent groundwater abstraction strategy

north and the Bay of Bengal in the south, with all boundaries extending to the base of the model. Closed and constant head boundary conditions are imposed along the northern and the western boundaries, demarcated by the Titas and Meghna Rivers which form large, permanent hydrological features (i.e., their width varies from < 1 to ~ 10 km from north to south of the region) in hydraulic contact with the aquifer. These boundary conditions allow free flow of water into and out of the model domain depending on the head simulated at each of the model layers (Zahid et al. 2015). Along the eastern boundary, a no-flow condition is imposed, the Tertiary sediments of the Tripura hills being considered to allow negligible flow in comparison to the unconsolidated, alluvial sediments of the Bengal Aquifer System (Michael and Voss 2009a). A fixed, constant head is assigned along the southern boundary of the model domain where it borders the Bay of Bengal.

Groundwater abstractions in the model account for domestic and agricultural demand as noted in Table 2 and illustrated in Fig. 2. Regionally, there are very few observations of groundwater heads in the Bengal Aquifer System in the depth range 150–350 m bgl. Due to this lack of observed groundwater head data from multiple depths of the aquifer system (e.g., model layers 6 and 7), limited calibration was conducted using the observed heads from Kachua (located in the center of the model area) as weekly monitored groundwater levels (year 2004) from a number of boreholes. The range of mean simulated heads (3–3.5 m) falls largely within the range of observed heads (3–8 m) within the three model aquifer units (Zahid 2008). Furthermore, the model was validated regionally against groundwater heads monitored by the Bangladesh Water Development Board at shallow levels, < 75 m depth within the study area (BWDB 2005; Zahid 2008; Zahid et al. 2015) for the depth-distributed pumping scenario with pumping quantities for 2004 (BADC 2005). Additionally, Burgess et al. (2017) show that groundwater levels in BAS are greatly influenced by terrestrial water

Table 2 Abstraction quantities and their depth distribution as applied in the 'depth-distributed pumping' scenarios

Abstraction mode	Model depth (m bgl)	Estimation basis	2004 rate (model area) (m year^{-1})	2050 rate (model area) (m year^{-1})
Shallow domestic pumping	16–46	Per capita use of 25 l per day	0.011	0.017
Shallow irrigation pumping	46–76	Total number of shallow irrigation pumps; pumping rate of 50 m^3/h for 8 h a day during November–May	0.253	0.292
Deep irrigation pumping	101–176	Total number of deep irrigation pumps; pumping rate of 200 m^3/h for 8 h a day during November–May	0.079	0.091
Deep domestic pumping	176–286	Per capita use of 6 l/day	0.003	0.004

loading and unloading at the surface and thus calibration of numerical models of transient groundwater flow using groundwater-level records is questionable. To support its application in simulating solute transport to deep levels in the aquifer, the model was therefore also calibrated against age determinations for deep groundwater in the region (Hoque and Burgess 2012) using hydraulic conductivity and effective porosity as calibration parameters. Statistically significant ($R^2 = 0.76$, p value < 0.05) correspondence between groundwater ages derived from carbon-14 isotope data (Hoque and Burgess 2012) and modeled travel times (Fig. 3) suggests that the model performance is reasonable for considering simulated travel time for the analysis of deep groundwater security.

Abstraction strategies and scenarios

The two groundwater abstraction strategies (depth-distributed pumping and deep pumping) were analyzed with reference to eight scenarios:

Scenario 1	Nil pumping, representing natural, pre-development conditions.
Scenario 2	Depth-distributed pumping, 2004 quantities.
Scenario 3	Deep pumping, 2004 quantities.
Scenario 4	Depth-distributed pumping, 2050 quantities.
Scenario 5	Deep pumping, 2050 quantities.
Scenario 6	Depth-distributed pumping, 2004 quantities (discontinuous aquitard)
Scenario 7	Depth-distributed pumping, 2004 quantities (homogeneous aquifer system).
Scenario 8	Deep pumping, 2004 quantities (homogeneous aquifer system).

Scenario 1 represents natural, pre-development conditions without any pumping stresses applied. Scenarios 2 and 4 apply the 'depth-distributed' strategy with abstraction quantities for 2004 and 2050, respectively. This strategy is similar to the 'split-pumping' condition of Michael and Voss (2008), and is the de facto current situation. Domestic abstractions are from shallow hand-pumped tube wells (HTWs), deep hand-pumped tube wells (DTWs), and intermediate and deep wells using motorized pumps; irrigation water is pumped from intermediate depths. In contrast, a hypothetical 'deep pumping' strategy takes all abstractions, domestic and agricultural combined, from groundwater at a depth of 200–250 m bgl. This strategy is similar to the 'deep pumping' condition of Michael and Voss (2008). Scenarios 3 and 5 apply the 'deep pumping' strategy with abstraction quantities for 2004 and 2050, respectively. Scenario 6 explores the implications of lateral aquitard discontinuity, represented indicatively as windows of relatively high hydraulic conductivity distributed within the aquitard model layers, applying the 'depth-distributed pumping' strategy with abstraction quantities for 2004. For comparison with a single, homogeneous anisotropic aquifer representation, Scenarios 7 and 8 apply to all model layers the hydraulic conductivity characteristics of the single aquifer representation of the Bengal Aquifer System developed at basin scale (Michael and Voss 2009a), in which geological variability is represented by anisotropy with a K_h/K_v ratio of 10^4.

Abstraction quantities for domestic and irrigation use were estimated from population census data and irrigation coverage at the upazila level for 2004 (Zahid 2008; Zahid et al. 2015). Abstraction quantities and their depth distribution as applied in the 'depth-distributed pumping' scenarios are summarized in Table 2. The spatial distribution of groundwater abstraction for domestic supply and irrigation,

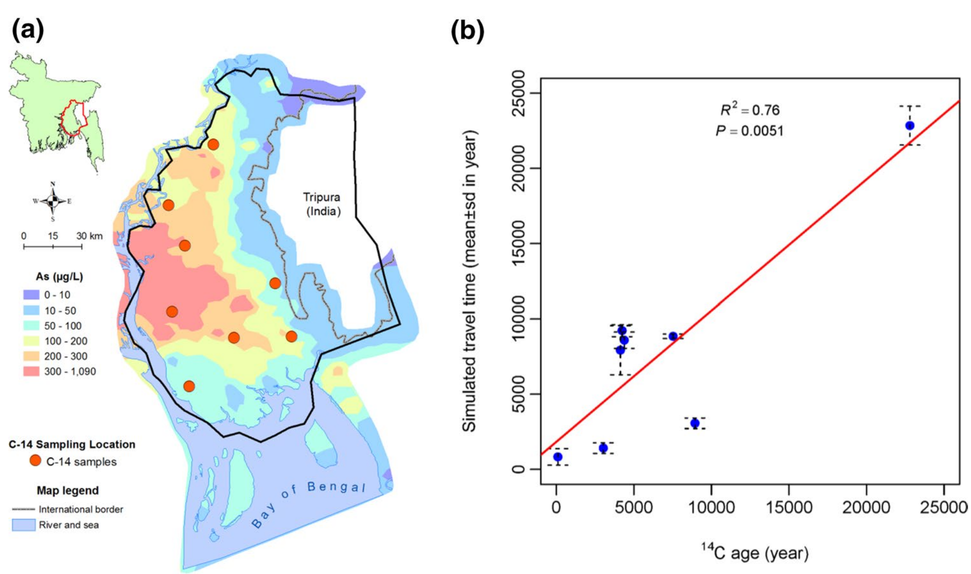

Fig. 3 Correspondence between groundwater ages to depth > 200 m bgl and modeled travel times for scenario 2 (depth-distributed pumping, 2004 quantities). Groundwater ages are from Hoque and Burgess (2012)

by upazila, is illustrated in Fig. 2. Shallow groundwater abstraction from hand-tube wells (HTWs) for household water supply in 2004 (scenario 2) is estimated (Zahid 2008; Zahid et al. 2015) as an equivalent water depth of 0.011 m year^{-1}, based on an estimated annual groundwater use of 9 m^3 per person. The comparable estimate over the entire Bengal Basin by Michael and Voss (2008) is a uniform abstraction of 0.019 m year^{-1}. Deep groundwater abstraction (> 200 m bgl) of 0.003 m year^{-1} was applied in scenario 2, representing 25% of total domestic water supply in the model area (Zahid 2008; Zahid et al. 2015). Irrigation abstraction is estimated for 2004 at 0.332 m year^{-1} (shallow irrigation: 0.253 m year^{-1}; deep irrigation: 0.079 m year^{-1}) total over the study area, based on the reported number of irrigation pumps (BADC 2005) and an estimated daily pumping rate of 8 h over the irrigation period of November to May (Zahid 2008; Zahid et al. 2015). The comparable estimate over the entire Bengal Basin by Michael and Voss (2008) is 0.21 m year^{-1}. In the future abstraction scenarios for 2050, domestic abstractions were increased according to the projected growth in population (Streatfield and Karar 2008), and irrigation abstraction was increased according to a projected rise in irrigation coverage in the region from 75% at present to 90% by 2050 (UCL 2013).

Analytical approach

Using a similar approach to that of Michael and Voss (2008) in assessing the 'flow pattern defense' against ingress of As, we based the determination of groundwater security on analysis of flow paths to points at depth in the aquifer, the presence/absence of excessive As in the flow path recharge area, and the time duration of flow from recharge to each point of determination. We discounted sorption, which is expected to retard arsenic movement relative to water (Radloff et al. 2011), particularly where iron oxyhydroxides, strong adsorbers of As, exist. There is debate over the magnitude of the effect of sorption in practice (Stollenwerk et al. 2007), but in omitting sorption our assessment is conservative and incorporates a factor of safety equivalent to the retardation that sorption would impose. In parallel with the security assessment and as a cautionary step, we indicate where the shallow water table is lowered to > 12 m bgl (Rahman and Ravenscroft 2003) for each groundwater pumping scenario investigated, but we do not include this a security criterion as the model is not designed to simulate the very shallow (< 25 m bgl) water table accurately, as the top of the model boundary is set to topographic elevation rather than as a specified flux in representation of the actual recharge process.

The areal extent of excessive As concentration in groundwater (> 50 µg L^{-1}) at shallow depth (Fig. 1) was derived by interpolation of the findings of the National Hydrochemical Survey of Bangladesh (BGS and DPHE 2001; DPHE 1999). For each of the eight groundwater abstraction scenarios (below, and Table 3), we first generated groundwater flow paths between the recharge origin at the ground surface and the deeper part of the aquifer system, applying particle tracking within the groundwater flow fields using the MODFLOW post-processor MODPATH (Pollock 1994). To map the security of deep groundwater against the invasion of As from contaminated shallow groundwater (< 150 mbgl), particles were tracked in a backward direction from the target depth of 190–200 m bgl m to the point of origin (i.e., location of groundwater recharge). Simulated flow paths (n = 2350–3415) were determined to an array of target zones at a depth of 190–200 m bgl, regularly spaced on a rectangular grid (n = 336) with a separation distance (from center to center) of approximately 7 km across the entire model domain (Fig. 1), each target zone representing a surface area of ~ 10 km^2. Flow path descriptors (e.g., geographic coordinates of the flow path origin, trajectory, length) were compiled and interpreted in terms of the security criteria by application of code written in the 'R' language (R Core Team 2017).

A similar approach of groundwater path line analysis was used to map the security of deep groundwater against

Table 3 Summary of the simulated groundwater flow path characteristics of all modeling scenarios. Descriptive summary statistics are calculated using all grid points (n = 336)

Modeling scenario	Number of flow paths	Mean flow path length (km)	Median travel time (years)	% Flow paths < 100 years	% Flow paths < 1000 years
1. Nil pumping	2351	38.6	3314	0.0	34.2
2. Depth distributed, 2004	3414	14.5	608	0.1	62.2
3. Deep pumping, 2004	3414	1.8	143	33.0	98.1
4. Depth distributed, 2050	3414	13.3	518	0.4	67.5
5. Deep pumping, 2050	3414	1.7	128	38.1	99.2
6. Discontinuous aquitard, 2004	3414	9.5	346	11.2	73.9
7. Homogeneous aquifer, depth distributed, 2004	3414	53.8	853	0.0	53.6
8. Homogeneous aquifer, deep pumping, 2004	3414	9.3	124	27.9	99.9

the potential invasion of salinity from shallow and intermediate depths. The spatial distribution of shallow sources of salinity (the salinity source term) was interpolated taking electrical conductivity (EC) as a proxy for salinity and using data extracted from contour maps of shallow (< 34 m bgl) groundwater EC (BADC 2012) and regional illustration of salinity distribution in deep irrigation tube wells (MMI 1992). The limit for EC is taken to be ≥ 1000 µS cm^{-1} at the points of recharge, approximately relating to the US Environmental Protection Agency (EPA) guideline for chloride concentration in drinking water. We have taken this empirical approach, rather than addressing the question of direct saline intrusion to deep groundwater from the Bay of Bengal as developed in the recent World Bank Report (Yu et al. 2010), taking the great depth of occurrence of fresh groundwater in the coastal areas as evidence for an effective hydraulic barrier between the present day marine and deep terrestrial groundwater systems.

Criteria for deep groundwater security mapping

In discussion with water resource managers, stakeholders and policy makers in Bangladesh (UCL 2013), we selected a 100-year time period for determination of security of deep groundwater and comparison of alternative pumping scenarios, consistent with the arguments toward sustainable groundwater use (Gleeson et al. 2012). We set criteria to describe the deep groundwater security with reference to the outcomes of particle tracking for each scenario, with deep groundwater defined as secure against As contamination where (a) it is predominantly (> 90%) sourced from recharge areas where As is at low concentration (As < 50 µg L^{-1}) and (b) otherwise, and where it is sourced from areas of excessive As concentration (As > 50 µg L^{-1}), the median travel time along flow paths from recharge to the point of analysis is > 100 years. We use the median travel time for the security assessment of deep groundwater as the mean value is biased toward the highest values associated with exceptionally long (> 50,000 years) flow paths.

Results

Summary statistics of groundwater flow paths and travel times for each modeled scenario are given in Table 3 and Fig. 4. Flow paths to grid points 190–200 m bgl in the

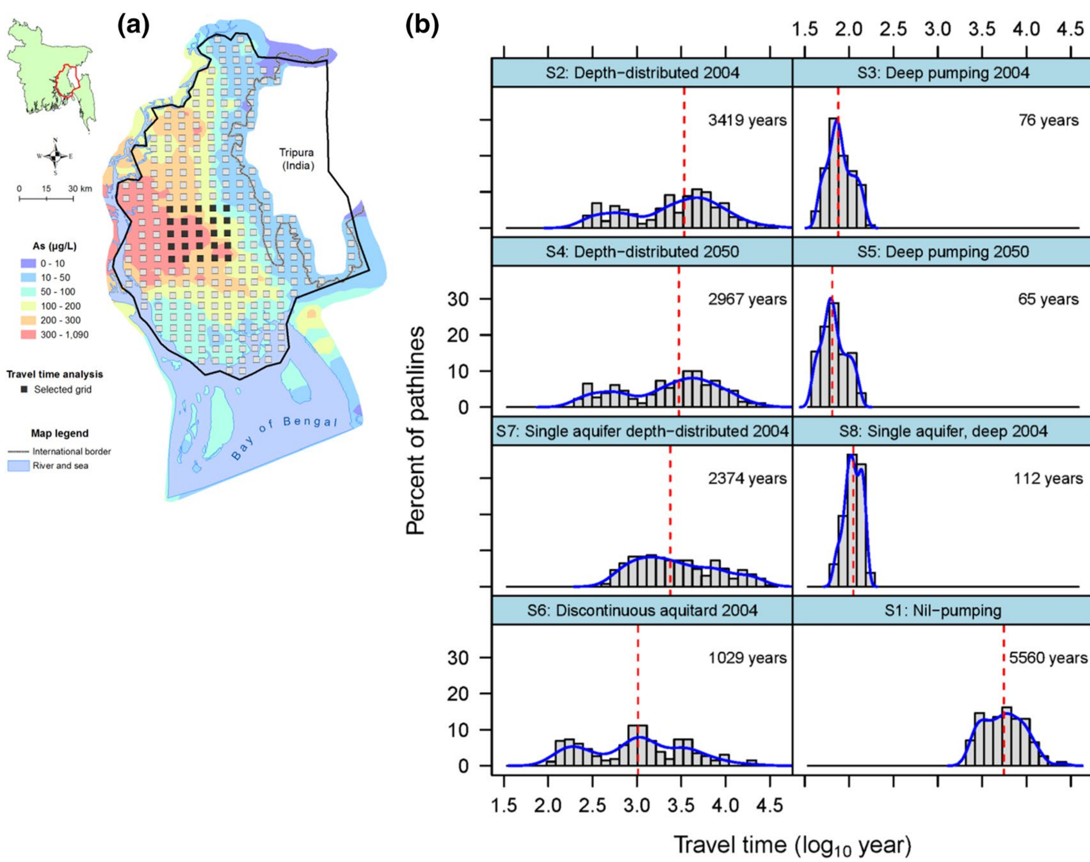

Fig. 4 Histograms showing the distribution of simulated travel times (year). Eight groundwater abstraction scenarios for the selected grids ($n = 25$) located in the central part of the model domain. Blue line—density distribution curve; red line—mean travel time

aquifer under pre-development conditions (nil pumping, scenario 1), depth-distributed pumping, 2004 quantities (scenario 2) and deep pumping, 2004 quantities (scenario 3) illustrate the effects of the two groundwater pumping strategies (Fig. 5). Figure 6 shows the spatial extent of the security of deep groundwater against arsenic under the two groundwater abstraction strategies for 2004 pumping quantities. The pre-development (nil pumping) condition provides the natural baseline. The pre-development pattern is of long groundwater flow paths deriving from recharge in the distant hilly regions at the basin margins. We find that the simulated flow path direction and length are highly sensitive to groundwater abstraction, aquifer properties, particularly K_h/K_v anisotropy, and the distribution of low-permeable layers. However, the choice of grid resolution is found to be less sensitive to the median travel time. The median groundwater travel time of our model (grid area ~ 6 km^2) to points at depth 190–200 m bgl across the model domain is 3070 years, similar (median of 3600 years) to that derived from modeling at basin scale with coarser grid resolution of 25 km^2 (Michael and Voss 2009a), and comparable to the range of ^{14}C-derived ages for groundwater in the study region at a depth ~ 150–340 m bgl (Hoque and Burgess 2012). The mean curvilinear trajectory length of simulated flow paths across the model domain is 38.6 km. All flow to 190–200 m depth has a travel time > 100 years; 34% of flow paths have a travel time < 1000 years in this marginal region of the basin.

The natural condition is much perturbed by pumping under both of the groundwater pumping strategies. Under depth-distributed pumping (scenario 2), a significant proportion of flow paths to deep abstraction points is derived locally. The statistical distribution of groundwater travel times to 190–200 m depth for a sub-set of grid points ($n = 25$) central to the model domain within the grossly As-affected area is very broad with flow paths ranging from ~ 100 years to > 30,000 years for the depth-distributed scenarios but much tighter for deep pumping scenarios (Fig. 4). The distributions of travel times for all eight scenarios aggregated over all target grids ($n = 336$) can be found in Figure S1 in the

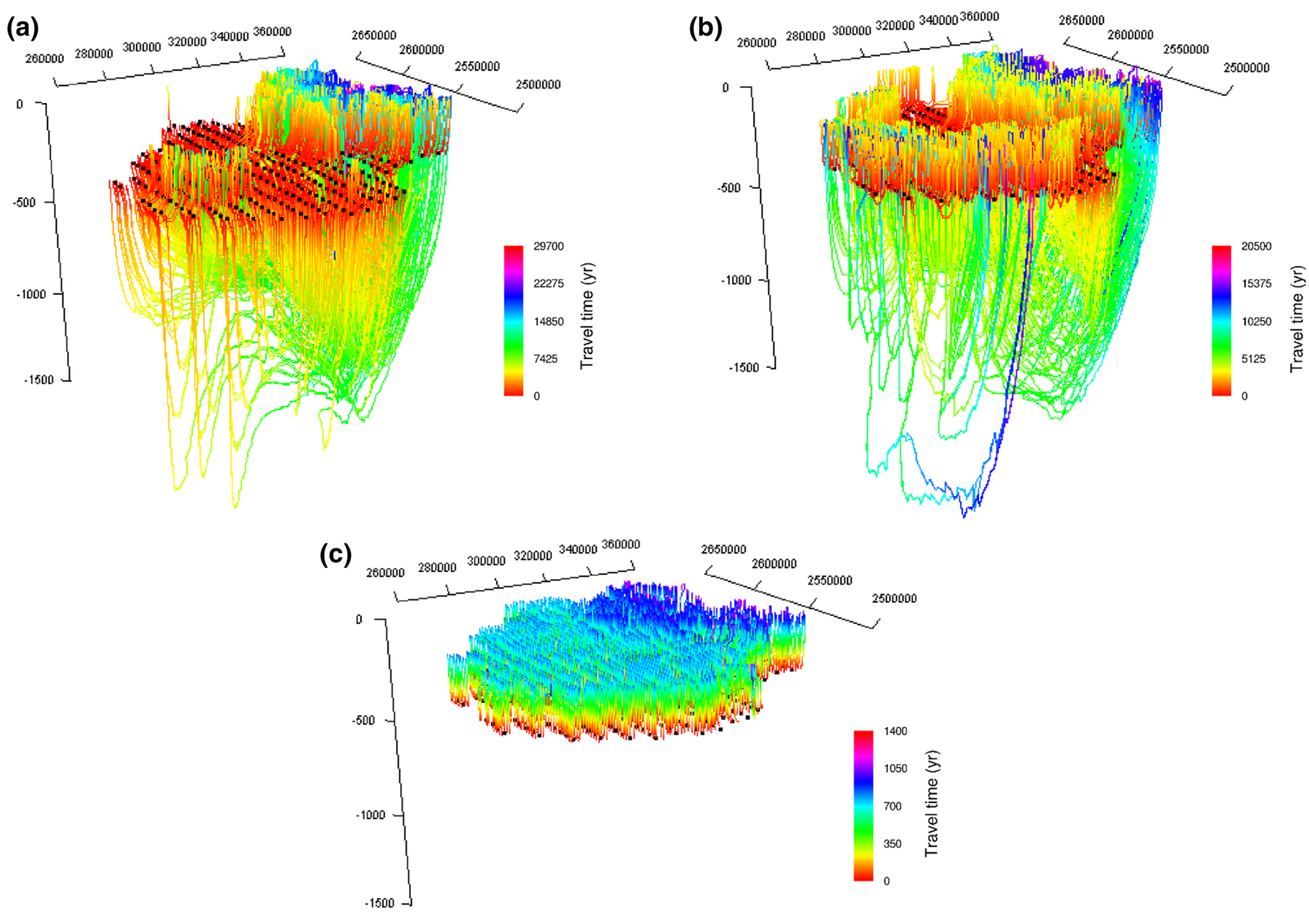

Fig. 5 Simulated groundwater flow paths back-tracked from points at depth 190–200 m bgl to the point of origin by MODPATH particle tracking post-processing under **a** pre-development conditions (nil pumping, scenario 1), **b** depth-distributed pumping, 2004 quantities (scenario 2), and **c** deep pumping, 2004 quantities, (scenario 3)

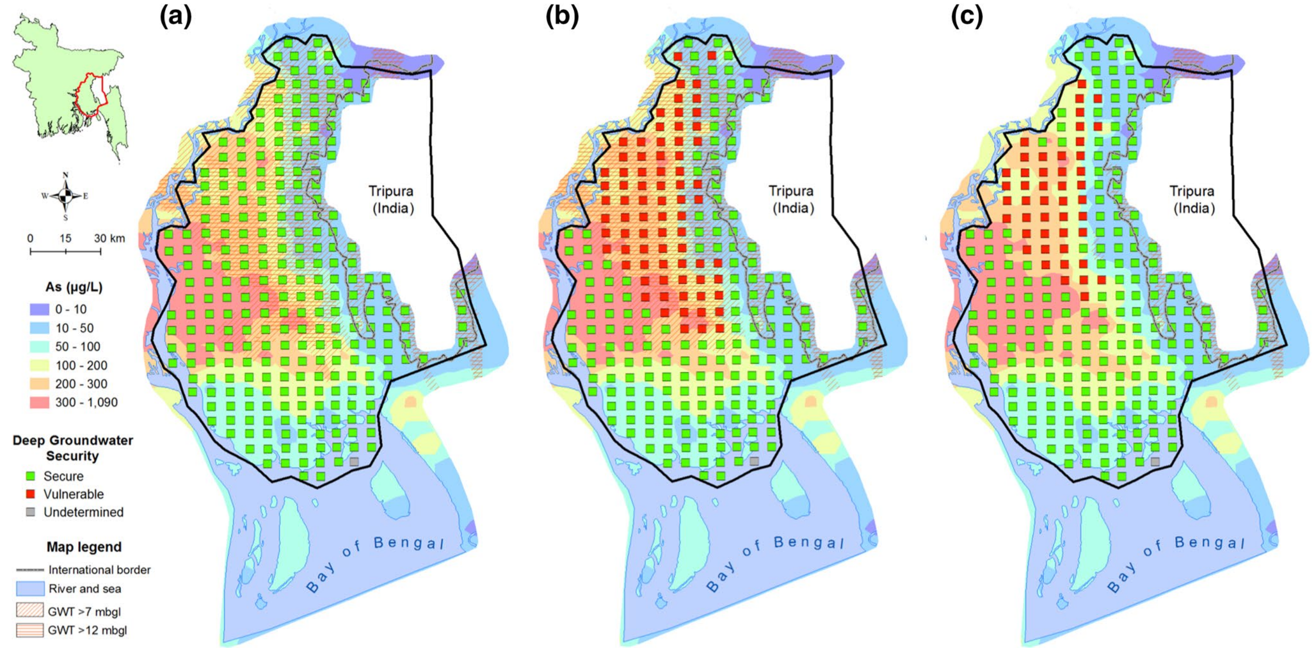

Fig. 6 Maps of deep groundwater vulnerability to shallow arsenic under **a** depth-distributed pumping, 2004 quantities (scenario 2), **b** deep pumping, 2004 quantities (scenario 3), **c** deep pumping, 2004 quantities, homogeneous aquifer system (scenario 8)

Supplementary Material. The mean distance from recharge areas to deep points of abstraction is reduced to nearly one-third of the mean path length under pre-development conditions, and much shorter travel times result; the median is close to 590 years. However, fewer than 1% of deep groundwater flow paths have a travel time of < 100 years under this scenario, indicating by the criteria applied here the security of the depth-distributed pumping strategy against invasion of As across the entire region (Fig. 6). The strategy remains secure to the same spatial extent under 2050 pumping quantities (scenario 4), for which the median travel time to deep points of abstraction remains over 500 years, and the proportion of deep groundwater flow paths with a travel time < 100 years remains below 1%. Lateral aquitard discontinuity (scenario 6) allows additional short flow paths (Table 3; Fig. 5) which render the deep groundwater abstractions more vulnerable to contamination from shallow levels, but this is also less extreme than the impact of the deep pumping strategy (Table 3; Fig. 5). The flow path bi-modality induced under the depth-distributed pumping strategy is more exaggerated under the multi-layered aquifer representation (Fig. 4, scenarios 2 and 4) than the single homogeneous aquifer representation (Fig. 4, scenario 7), indicating that the deterministic hydrostratigraphy of Zahid (2008) has a greater K_h/K_v anisotropy effective at the regional scale than the equivalent single aquifer representation at the basin scale by Michael and Voss (2008).

The effect of the hypothetical deep pumping strategy is more extreme (Figs. 4, 5; Table 3). Under this strategy, all deep groundwater pumped is ultimately derived locally, the mean flow path length is 1.7 km and the median groundwater travel time from the surface to deep points of abstraction is reduced to less than 150 years. 33% of flow paths under the deep pumping strategy (2004 quantities, scenario 3) have a travel time to points at 190–200 m depth of < 100 years. Against the 100 -year benchmark, the deep pumping strategy is indicated as a potentially secure water supply option in relation to As over only part of the south and west of the study area, and this is so also at 2050 pumping quantities (see Figure S2 in the Supplementary Material). Note that the strategy would not be accepted against a 1000-year benchmark policy requirement for safe supply, close to 100% of groundwater flow paths to 190–200 m depth having travel times < 1000 years.

Discussion

The present assessment of deep groundwater abstraction strategies in southeast Bangladesh follows an approach similar to assessment of the 'flow-pattern defense' at the scale of the whole basin by Michael and Voss (2008) but at a finer grid scale (mean distance among conjoining grids is approximately 2.5 km), using a six-layered hydrostratigraphy to represent the Bengal Aquifer System, and applying spatially distributed pumping stresses. The 'split pumping' strategy of Michael and Voss (2008) distributes current domestic water use as deep tube well abstraction evenly across the basin; the present analysis, being based on population density, effectively includes municipal pumping, and applies future abstraction rates up to those estimated for 2050. Critically, the present assessment applies a 100-year benchmark time scale for security of water supply from deep groundwater, against the 1000-year benchmark of Michael and Voss (2008), as water managers and policy makers in Bangladesh expressed their primary interest in developing strategies over a shorter planning time frame.

There is consensus between the two scales of analysis on the overall conclusion that deep groundwater abstraction offers a secure option over extensive regions, when it is restricted to public water supply, i.e., under a depth-distributed pumping strategy. The present results do, however, provide a cautionary perspective: discontinuity in the aquitard layers, for which there is evidence from groundwater head monitoring and lithological logs, has the potential to render deep groundwater locally vulnerable to earlier ingress of As (scenario 6) than would otherwise be expected (scenario 2), even under present-day pumping quantities (Table 3; Fig. 4), as also indicated by geostatistical representation of aquifer heterogeneity in the vicinity of Dhaka (Khan et al. 2016). The analysis of heterogeneity here is indicative; a more thorough treatment of spatial heterogeneity in hydraulic conductivity (Hoque 2010; Hoque et al. 2017) could be the basis for a deterministic assessment of the implications of lithological variability on deep groundwater vulnerability (UCL 2013). Also, the effects of locally focused abstraction of deep groundwater for municipal supplies are not individually represented. In both these instances, the local effects on As migration might be more extreme than is evident in this regional assessment.

These modeling indications are consistent with a study in the coastal BAS using chemical tracers and isotopic indicators of groundwater age (Lapworth et al. 2018), which reveals that groundwater below a depth of 150 m is 1000–10,000 years old and contains no modern components except where associated with short-circuiting of vertical leakage within inadequately sealed pumping boreholes. At all locations, especially at those identified as more vulnerable to vertical migration of As from shallow depth, deep groundwater use should be restricted to domestic supply, preferably by hand-pumped tube well, and monitored closely.

The present analysis also finds that under the deep pumping strategy, almost all groundwater flow paths to 190–200 m have travel times < 1000 years, concluding in common with Michael and Voss (2008) that deep pumping for the combined requirements of domestic water supply and irrigation over this very long time scale would lead to widespread degradation of the deep groundwater resource. The modeling results show much the same outcome under a 100-year benchmark, despite suggesting that high-capacity deep groundwater pumping for combined domestic and irrigation demands may potentially be a secure water supply option in relation to As over part of the south and west of the study area, even at rates estimated for 2050 (see Figure S2 in the Supplementary Material).

The analysis concentrates on security against As incursion, but in some coastal regions of Bangladesh salinity of groundwater at shallow and/or intermediate depths (Hoque et al. 2003; Zahid et al. 2013) is an additional constraint on use of groundwater for water supply, unrelated to As and less thoroughly determined (DPHE/DANIDA 2001; Ravenscroft and McArthur 2004). Deep groundwater pumping for public water supply at Khulna and Barisal in coastal Bangladesh over the past three decades has had no adverse outcomes for salinity or As (Ravenscroft et al. 2013). Despite the need for caution where locally there may be no hydraulic barrier to vertical flow, the evidence encourages the conclusion that deep groundwater abstraction offers a secure option over extensive regions, when it is restricted to public water supply. Where there are shallow sources of both As and salinity, intensive pumping of deep groundwater would be expected ultimately to induce invasion of saline groundwater before As breakthrough at deep wells, due to the retarding effect of As sorption (Radloff et al. 2011). However the estimated extent of excessive salinity overlaps the sub-region of deep groundwater security in scenario 3 (Fig. 7) and conspires against the overall security of the deep pumping strategy.

Possibly, the greatest simplification in all groundwater flow models of the Bengal Basin which explore long-term behavior (Michael and Voss 2009a; Mukherjee et al. 2007; Zahid et al. 2015) is the lack of acknowledgment of temporal evolution of the aquifer itself. Substantial portions of the Bengal Aquifer System, from surface to approximately 100 m depth, have been deposited within the past 10,000 years (Burgess et al. 2010). The hydraulic base level of the aquifer in reality has been substantially modified over the time period (Hoque et al. 2017) that the models simulate large-scale groundwater flow. This complexity, and the implications for solute transport in an evolving aquifer framework, has not been addressed in the current work. This and other simplifications and uncertainties inherent in groundwater flow modeling at this scale will result in error and uncertainty in the model results. Nevertheless, the model successfully reproduces the sparse existing data on groundwater head to depths of 300 m and simulates groundwater ages in reasonable agreement with the few independent observations available. The results are therefore indicative and offer a quantifiable basis for drawing conclusions to assist policy development.

For policy makers, we emphasize that deep groundwater provides a source for long-term secure water supply in southern Bangladesh. In its ability to mitigate the effects of arsenic and salinity in shallow groundwater, it has enormous

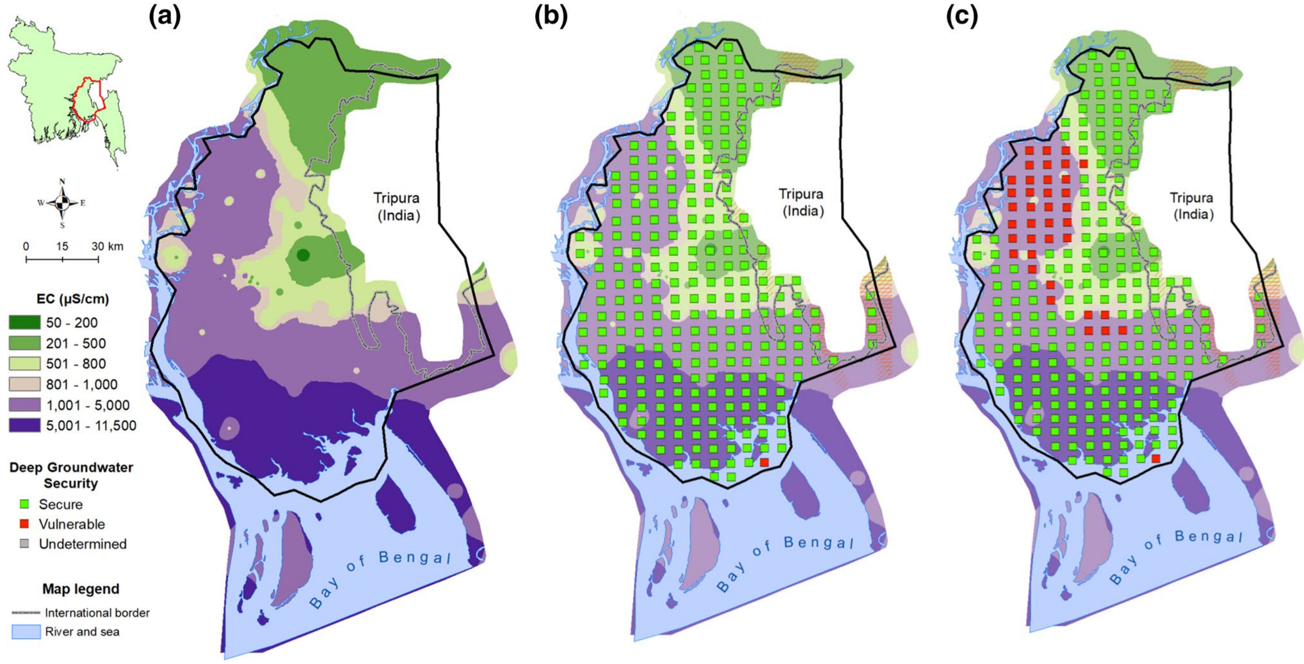

Fig. 7 **a** The estimated extent of excessive salinity at shallow and intermediate depth. Sources of salinity data: BADC (2012) and MMI (1992), **b** depth-distributed pumping, 2004 quantities (scenario 2), and **c** deep pumping, 2004 quantities, (scenario 3)

strategic value for water supply, health protection and development. Where adverse impacts may locally be induced earlier than the 100-year benchmark of security, they will be manageable within a robust framework of groundwater monitoring. We emphasize that monitoring should provide adequate warning of adverse effects, and that sorption may in any case substantially delay arsenic incursion and increase the time available for a managed response. Sentinel monitoring could provide many years advance warning of impending problems. Boreholes for monitoring groundwater head and electrical conductivity, and for collection of samples for monitoring groundwater chemistry, should be located at all main urban locations in close vicinity to pumping tube wells, and completed at intermediate depths as well as the depths of pumping. Similar monitoring points should be installed in rural areas at the locations of irrigation programs targeting deep groundwater and at abstraction depths in the local vicinity of pumping boreholes. Monitoring should be required at all deep municipal water supply boreholes, and field test kits should be essential for private well owners (van Geen et al. 2005).

Ultimately (e.g., after 1000 years, or longer), deep groundwater may be vulnerable if subjected to excessive pumping, but for a considerable time (at least 100 years) careful, properly monitored deep groundwater pumping for public water supply could support regional development, giving time for long-term goals to be realized. This time period for water supply security offers a safe arsenic mitigation option and decline in arsenic exposure for many millions of people in southeast Bangladesh, and gives an opportunity to achieve longer-term strategic goals for distributed public water supply with centralized treatment in urban locations. Deep groundwater pumping for irrigation, currently very limited in SE Bangladesh, noticeably restricts the regions of deep groundwater security and as a cautionary principle consideration should be given to reserving deep groundwater for drinking water supply.

It is well documented that shallow groundwater (< 150 m bgl) in other Asian mega-deltas is contaminated with excessive concentrations of As (Fendorf et al. 2010). Winkel et al. (2011) report that long-term (> 100 years) pumping of deep groundwater in urban areas of the Red River Delta has indeed induced migration of As from shallow depths. A recent modeling study in the Bengal Basin with a special focus on municipal pumping in Dhaka City shows that large-scale drawdown in and around the city limits might contaminate deep (> 150 m bgl) groundwater with As within a decade through preferential flow paths typical of fluvio-deltaic aquifers in Asian Mega-Deltas (Khan et al. 2016). In other deltas (e.g., Mekong River Delta, Irrawaddy River Delta) the use of groundwater is currently limited to shallow aquifers (Fendorf et al. 2010); however, the pressure on deep groundwater will increase as an adaptive strategy in the face of climate change and increasing demand for both drinking and irrigation water supplies (Taylor et al. 2013). The methods presented here can be applied in other Asian mega-deltas to map the security of deep groundwater against the ingress of As and salinity from shallow depths.

Conclusions

Water supply engineers, regulators, policy makers and development scientists in Bangladesh recognize the strategic value and beneficial health impacts of deep groundwater free of excessive As and salinity. Therefore, they will consider groundwater development strategies that offer security of supply for a sufficient period of time, even if they are ultimately unsustainable. We have applied criteria including a 100-year benchmark in mapping the security of deep groundwater against ingress of As in SE Bangladesh under two strategies, depth-distributed pumping and deep pumping, with domestic and agricultural pumping quantities estimated for recent (2004) and future (2050) times, making reference to eight modeled groundwater pumping scenarios. Our analysis is founded on the concept of time-limited security in relation to a groundwater pumping strategy, in place of strict sustainability. Deep groundwater is secure against invasion of As and salinity for in excess of 100 years across the entire region, even under domestic demand estimated for 2050, if it is restricted to domestic supply, including deep pumping both for municipal supplies and private supply using deep hand-pumped tube wells (the depth-distributed pumping strategy). Deep groundwater pumping for irrigation noticeably restricts the regions of security. Although this modeling study indicates that use of deep groundwater for combined irrigation and domestic demands (the deep-pumping strategy) is potentially secure against As invasion only over a small part of southeast Bangladesh, even at rates estimated for 2050, a precautionary approach would be to restrict deep groundwater abstraction to domestic water supply only, on account of vulnerability to As invasion over most of the region if deep irrigation pumping was to be allowed.

Two aspects underscore the need for caution and further study. Local discontinuity in aquitard layering renders deep groundwater locally vulnerable to early ingress of As even under present-day pumping quantities. Also, the sub-region in southeast Bangladesh shown to be secure under the deep-pumping strategy is partially co-incident with the occurrence of saline groundwater at shallow and/or intermediate levels in the aquifer system. Here, the security of deep pumping may be compromised by the additional threat posed by salinity. We have estimated the spatial extent of groundwater salinity at shallow and intermediate depth in southeast Bangladesh, showing it likely to exceed the accepted limits for chloride in drinking water up to several tens of kilometers inland from the coast and along the line of the Meghna River.

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. Suitable monitoring should provide adequate warning of adverse effects, and sorption may in any case substantially delay arsenic incursion and increase the time available for a managed and timely response. Ultimately, e.g., after 1000 years or longer, excessive pumping will lead to widespread pollution of the deep groundwater resource, but for a considerable time, at least 100 years, properly monitored deep groundwater pumping could support regional development, giving time for long term goals to be realized.

Deep groundwater is a potentially valuable resource to mitigate the calamitous health effects of excessive As in water supplies sourced from shallow groundwater in other extensive mega-deltas of southeast Asia, as in Bangladesh. There can be strategic and economic value, and ethical justification, in time-limited development of the deep groundwater resource, even though it may be unsustainable in the very long term.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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