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Delineating low-arsenic groundwater environments in the Bengal Aquifer System, Bangladesh

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ABSTRACT

Studies within the As-affected Bengal Basin have indicated that low-As groundwater can be found in a variety of geological and geomorphological settings. The hydrogeological environments that host low-As groundwater may be interpreted within a geological framework determined by the Quaternary evolution of the Bengal Aquifer System (BAS). This provides the basis for delineating the position and extent of shallow low-As groundwater, low-As groundwater in oxidised 'red-bed' sediments, and deep low-As groundwater. Data available on a national scale allow a preliminary delineation of these low-As groundwater environments across Bangladesh, based on empirical associations of low-As groundwater occurrences with topography, water table elevation, surface sediment lithology, geology and the screen depth of deep wells in low-As zones.

1. Introduction

Excessive As in groundwater, 10–100 times the WHO guideline for drinking water (10 μg/L), threatens human health and the yield of irrigated crops across the extensive floodplains of the Ganges, Brahmaputra and Meghna rivers of the Bengal Basin in West Bengal and Bangladesh (Smith et al., 2000; BGS/DPHE, 2001; Brammer and Ravenscroft, 2009; Das et al., 2009; Ravenscroft et al., 2009). Preliminary suggestions linking excessive As in groundwater to anthropogenic sources, groundwater irrigation (Mallick and Rajagopal, 1996) and fertiliser application (Acharyya et al., 1999) have been discredited (McArthur et al., 2001). A natural origin for the basin-wide extent of the groundwater As is widely accepted (Bhattacharya et al., 1997; Dhar et al., 1997; Nickson et al., 1998; BGS/DPHE, 2001; McArthur et al., 2001), although recent studies have suggested that irrigation practices can impact As concentrations in Bengal Aquifer System (BAS) groundwater locally (Harvey et al., 2006; Neumann et al., 2010). Elevated As is associated with the widespread reducing hydrochemical conditions (Bhattacharya et al., 1997) in grey-coloured sediments of Holocene age (McArthur et al., 2001) at depths <100 m (Bhattacharya et al., 1997; BGS/DPHE, 2001; van Geen et al., 2003b). It is widely accepted (Fendorf et al., 2010) that As is released to groundwater by microbially-mediated (Islam et al., 2004) reductive dissolution of the Fe-oxyhydroxide coating (Nickson et al., 1998) of sedimentary particles, in the presence of organic matter (Harvey et al., 2002; McArthur et al., 2004; Neumann et al., 2010). Within this environment, As concentrations nevertheless exhibit extreme spatial variability (DPHE/UNICEF/WB, 2000; van Geen et al., 2003b; McArthur et al., 2004), related at individual sites to the nature and availability of the organic-C substrate (Harvey et al., 2002; McArthur et al., 2004; Neumann et al., 2010), to local sedimentological controls (Burgess et al., 2002; Weinman et al., 2008; Hoque et al., 2009) and to patterns of groundwater recharge and flow (Stute et al., 2007; Aziz et al., 2008). Throughout Bangladesh, over 70% of 'shallow' tube-wells screened within 50 m of the ground surface (BGS/DPHE, 2001) supply 'low-As' groundwater. The term 'low-As' in relation to a water source is defined here as meaning <50 μg/L As, the regulatory limit for drinking water in Bangladesh and West Bengal of India, rather than 10 μg/L As, the WHO drinking-water guideline. Arsenic is essentially absent from groundwater in Plio-Pleistocene and older sediments of the basin (BGS/DPHE, 2001; van Geen et al., 2003b; McArthur et al., 2004, 2008).

The strategic importance of groundwater in the Bengal Basin and the threats posed by excessive As emphasise the significance of low-As groundwater sources and have prompted assessments of the hydrostratigraphy of the basin sedimentary sequences (Ravenscroft et al., 2005; Mukherjee et al., 2007; McArthur et al., 2008; Michael and Voss, 2008, 2009a; Burgess et al., 2010; Hoque, 2010). The BAS is recognised as comprising Pliocene to Holocene sediments which host a number of regional aquifers, hydraulically connected on a basin-wide scale (Burgess et al., 2010), in which multiple discontinuous layers of silty-clay impose an effective

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anisotropy across a range of scales (Michael and Voss, 2009b; Hoque, 2010). The structure and geological evolution of the BAS determines the hydrogeological contexts of the low-As groundwater environments. The objective of this paper is to estimate the spatial extent and depth range of the low-As groundwater environments across Bangladesh, by mapping their geomorphological and geological associations within the BAS.

2. Basin geomorphology and geology of the Bengal Aquifer System (BAS)

The Bengal Basin comprises most of Bangladesh and parts of West Bengal, India (Fig. 1), incorporating the Holocene–Recent floodplains of the Ganges, Brahmaputra and Meghna rivers and their tributaries and distributaries. Isolated Plio-Pleistocene inliers (Morgan and McIntire, 1959; Umitsu, 1993; Goodbred and Kuehl, 2000), with 10–30 m thickness of clay residuum at the surface, form elevated intra-basinal tracts (the Barind Tract and the Madhupur Tract) 30–50 m above mean sea level (MSL), and remnant Plio-Pleistocene sediments also occur along the basin margins (Fig. 1).

Regionally, the relatively high topographic gradient (0.35–0.25 m/km) of the alluvial fans in the north of the basin grades to a more gently-sloping (0.05–0.01 m/km) fluvial regime in the central regions and ultimately to the almost flat (0.01–0.001 m/km) tidal-delta setting in the south where ground elevation is <1 m

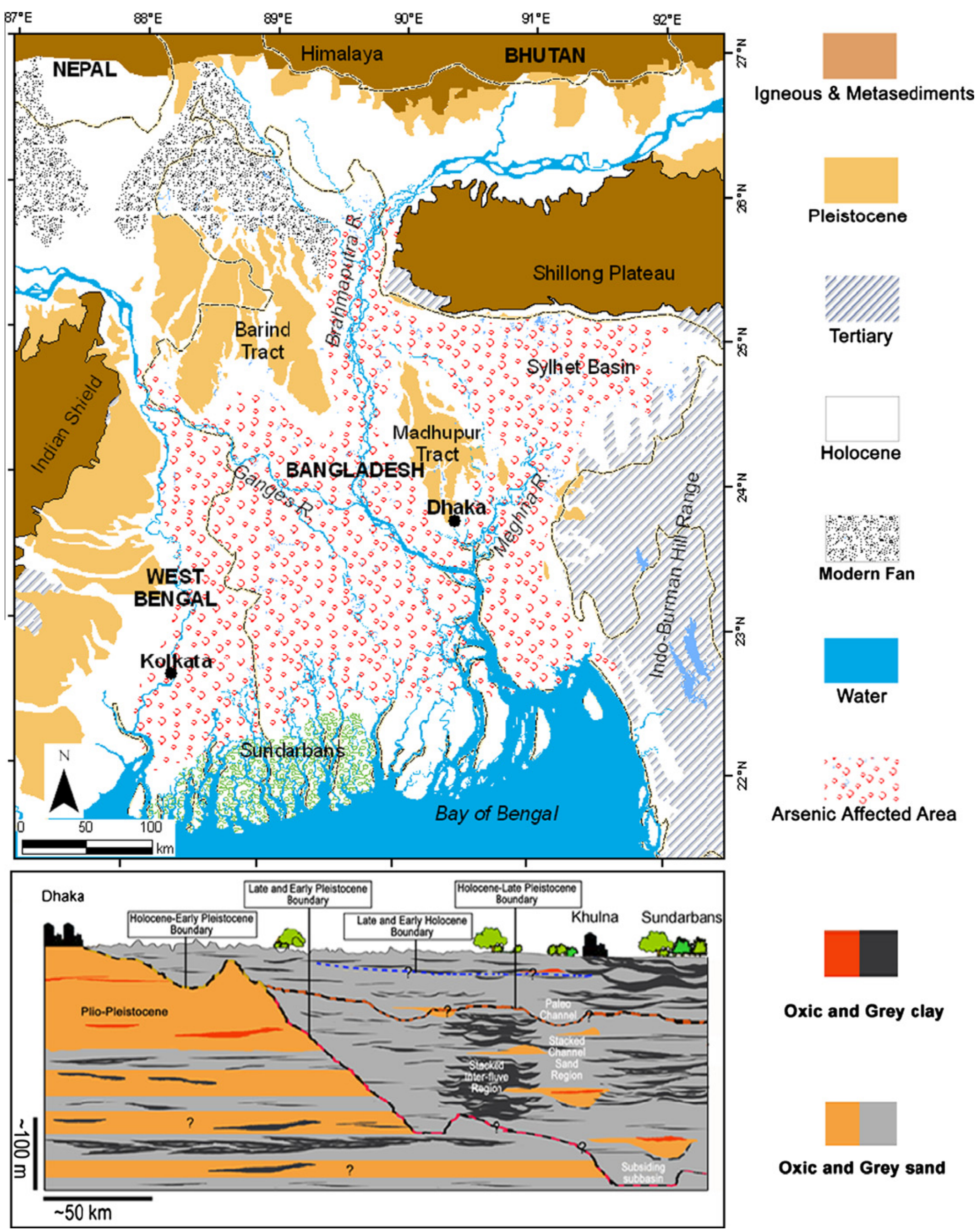

Fig. 1. (a) Bengal Basin: geography, major landforms, surface geology and extent of As-affected areas. (b) Aquifer hydrogeological framework – a conceptual bi-modal (sand–clay) representation of the aquifer environments in the Bengal Basin. Note that oxic (brown) and reduced (grey) lithologies of equivalent grain size have similar hydraulic properties (after Burgess et al., 2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

above MSL and the basin is open to the Bay of Bengal (Shamsudduha et al., 2009b). Predominant sediment grain size grades from coarse sand in the north to silty-clay in the south (van Geen et al., 2008). The subtle topographic relief provided by ridges and sloughs, the products of accretion and/or migration of river channels, has undergone modification for agricultural and other developments in recent decades.

The basin experiences a tropical monsoon climate (e.g., Sanderson and Ahmed, 1979), with a hot and rainy summer (June–September) and a drier winter (November–February). Basin-wide annual average rainfall is 1500 mm, with areas near the hills in the east and NE receiving in excess of 4000 mm. The high rainfall, the abundance of large rivers with many tributaries and distributaries, the extensive unconsolidated surface sediments, and a shallow water table together facilitate a dynamic hydrological system in the basin. Groundwater recharge is dominantly from rainfall (Stute et al., 2007). In recent decades the natural groundwater dynamics of the region have been greatly affected by the intensive abstraction for irrigation, and for industrial and domestic supply (Bhuiyan, 1984; Harvey et al., 2006; Hoque et al., 2007; Shamsudduha et al., 2009a).

The Bengal Basin contains a sedimentary sequence of Late Cretaceous–Recent age (Curray, 1991; Reimann, 1993; Alam et al., 2003) thickening from a few hundred metres at the basin margin, a palaeo-continental shelf in the NW, to >20 km in the SE. Detailed descriptions of the stratigraphy and sedimentation history of the basin are given by Reimann (1993), Alam et al. (2003), Uddin and Lundberg (2004), Mukherjee et al. (2009), and references therein. A summary description of the stratigraphy is presented in Table 1.

The BAS occupies the uppermost few hundred metres of the stratigraphic sequence, deposited since Mio-Pliocene time. The basin-wide Mio-Pliocene Upper Marine Shale probably acts as a hydraulic basement to the BAS at ca. 1200–2000 m depth, and the hydrogeological structure of the BAS is determined by the Pliocene to Holocene evolution of the basin (Burgess et al., 2010; Hoque, 2010), comprising a long history of alluvial/fluviatile/deltaic deposition (Ravenscroft, 2003) and basin subsidence (Goodbred and Kuehl, 2000). Together, these provide the geological basis for preservation of permeable sediments to depths of many hundreds of metres.

Formation of the BAS during the Quaternary took place under conditions of eustatic cyclicity, with deposition, subsidence and erosion occurring in channels and interfluves across the floodplain. Subsidence of 2 mm/a broadly across the basin (Goodbred and Kuehl, 2000) accommodated approximately 200 m of sediment over the past 1 Ma, this time interval incorporating 10 eustatic cycles (Lisiecki and Raymo, 2005) each with an effective sedimentation time of approximately 10 ka. Episodic eustatic sea-level low stands since the Early Pleistocene, to 130 m below present MSL (Caputo, 2007), drove periods of sustained weathering of the remnant Plio-Pleistocene sediment tracts through repeated flushing by meteoric water. This weathering history resulted in the regionally extensive oxidation of the Plio-Pleistocene terraces of the central and northern parts of the Bengal Basin, as reflected in the characteristically yellow-brown to red colour of these 'red-bed' sediments. Channel migration during the intervening periods of transgressive sea level rise partially eroded the oxidised Pleistocene sediments beyond the Plio-Pleistocene tracts, resulting in limited preservation and patchy occurrence of 'red-beds' buried beneath the Holocene–Recent floodplains; reducing conditions dominate the majority of these deeply buried Pleistocene sediments (Burgess et al., 2010; Hoque, 2010) (Fig. 1b and also see Fig. 5). Phases of pedogenesis under intermittent pauses in sea level rise and under the more sustained high-stand conditions (Kraus, 1999) appear to have been partially preserved as thin oxidised palaeosols in places (Monsur, 1995).

This sequence of unconsolidated Pliocene–Pleistocene–Holocene sediments hosts a number of regional aquifers that are hydraulically connected within the BAS on a basin-wide scale. The Mio-Pliocene Tipam sandstone serves as an aquifer in the eastern folded hills of the Chittagong Hill Tracts. The Plio-Pleistocene Dupi Tila sands form the main aquifer of the elevated Barind and Madhupur Tracts, and in the hilly region of Sylhet and parts of Chittagong. Holocene sands, silts and silty-clays beneath the active floodplains overlie Pleistocene sediments to a general depth of about 100 m in the south of the basin, forming the shallow aquifer that is grossly affected by excessive levels of As in groundwater. Pleistocene sediments buried beneath the Holocene sequence are host to deeper groundwater.

Hydrostratigraphic analyses (Mukherjee, 2006; Mukherjee et al., 2007; Hoque, 2010) indicate a ubiquity of discontinuous silt–clay layers within the predominantly sandy sediments of the BAS. These silt–clay layers, which are variable in depth, thickness, and extent, cannot be correlated laterally, but impart a hydraulic anisotropy to the basin sediments at a range of scales (Michael and Voss, 2009b; Hoque, 2010). Groundwater flow systems ranging from shallow to deep are developed, driven by topography (Tóth, 1963, 2009) and influenced by the anisotropy of hydraulic conductivity (Hoque, 2010). Groundwater flow modelling (Michael and

Table 1
Generalised stratigraphy of the Bengal Basin in Bangladesh (adopted from Alam et al., 1990, 2003; Dasgupta et al., 1993; Reimann, 1993; Ravenscroft et al., 2005).

Age	Stratigraphical unit	Lithology	Notes
Throughout, but mostly in the eastern part of the basin			
Holocene	Alluvium	Fining upward, unconsolidated grey micaceous, fine to medium sand with organic silty-mud and peat	Forms the shallow aquifer throughout the floodplains
Pleistocene	Madhupur/Barind clay Dihing Dupi Tila/(Debagram and Ranaghat)[a]	Yellowish-brown to light grey, medium and coarse sand to clay; very weakly consolidated; depleted in mica and organic matter	Forms major aquifers in the Pleistocene terraces, and deeper aquifer beneath the floodplains
Pliocene	Girujan clay Tipam/(Pandua)[a]	Yellowish-brown, weakly consolidated sandstone and mudstone	Forms minor aquifers in the eastern hills; includes the UMS (Upper Marine Shale), a regional aquitard
Miocene	Surma/Jamalganj/(Pandua)[a]	Alternating semi-consolidated sandstone and shale	
Well documented in the NW part of the basin			
Palaeogene			
Oligocene	Barail/Bogra/(Memari and Burdwan)[a]	Consolidated sandstone and shale	Forms minor aquifers in the northeast/Sylhet area
Eocene	Kopili shale Sylhet limetsone	Friable shale and limestone	No significant aquifer
Palaeocene	Tura/(Jalangi)[a]	Sandstone with coal fragments	
Cretaceous	Rajmahal	Basalt, shale and sandstone	
Permian	Gondwana	Sandstone and thick/thin coal seams	
Precambrian	Basement Complex	Gneiss and schist	

[a] Denotes equivalent unit of West Bengal, India.

Voss, 2009a; Hoque, 2010) has indicated that the BAS at >150 m depth in Bangladesh is hydraulically separate from the shallow aquifer, but no extensive impermeable layers provide continuous physical separation between the shallow and deeper regions of the aquifer. Michael and Voss (2009a) have represented the BAS as a single, homogeneous, anisotropic aquifer (K_h/K_z value 10^4) at the scale of the whole basin. Across the southern part of the basin, however, thick belts both of sand and of silty-clays, of limited lateral extent, result from the stacking of channel sands and adjacent interfluve sediments deposited under stable channel conditions spanning repeated eustatic cycles (Burgess et al., 2010). These features impose significant heterogeneity at the sub-basinal scale. A schematic representation of the structure of the BAS is given in Fig. 1b, providing the hydrogeological framework within which to consider the low-As groundwater environments in the basin.

3. Low-arsenic groundwater environments in BAS

Despite the widespread occurrence of excessive As in the groundwater of the BAS, low-As groundwater is encountered in a variety of environments (Fig. 2) (BGS/DPHE, 2001; von Brömssen et al., 2007; McArthur et al., 2008; Michael and Voss, 2008; Hoque et al., 2009; Burgess et al., 2010), from very shallow to very deep within the aquifer system (Fig. 3). Explanations invoking the influences of geochemical environment (McArthur et al., 2004), organic C availability (McArthur et al., 2004; Neumann et al., 2010), local sedimentology (Burgess et al., 2002; Ravenscroft et al., 2005; McArthur et al., 2008; Weinman et al., 2008; Hoque et al., 2009) and groundwater flow (Harvey et al., 2002; Michael and Voss, 2009a; Hoque, 2010) on the spatial variability of As have been developed for individual research sites. However, there is continuing uncertainty regarding the significance of C sources (Neumann et al., 2010), the As sorption capacity of aquifer sediments (McArthur et al., 2004; Stollenwerk et al., 2007) and temporal trends in As concentrations (Cheng et al., 2005; Burgess et al., 2007; Dhar et al., 2008).

Approximately 70% of shallow wells surveyed by BGS/DPHE (2001), defined as screened at a depth <50 m, have <50 μg/L groundwater As. Empirical associations of the variability of shallow groundwater As with land-surface topography (Shamsudduha et al., 2009b) and water-table gradient (Ravenscroft et al., 2005;

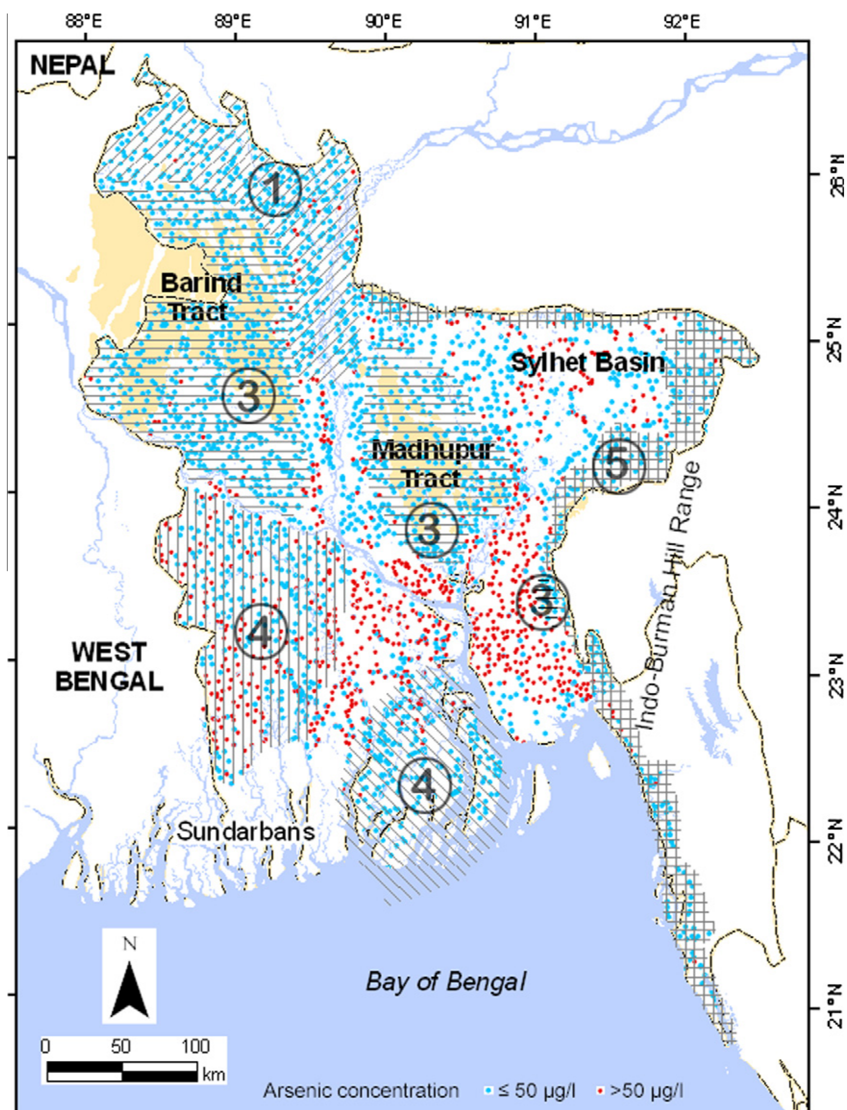

Fig. 2. Distribution of As-affected wells and identification of the low-As groundwater environments. Tubewell As data are from BGS/DPHE (2001). 1: Coarse-grained Holocene sediments in region of higher topographic gradient; 2: surficial sands (<30 m) in Recent and Holocene sediments throughout the basin (not shown, on account of extreme spatial variability – see text); 3: Plio-Pleistocene inliers; 4: within Holocene (<100 m depth) and Pleistocene (>150 m depth) sediments in the south of the basin, and in coastal regions (>250 m depth); 5: pre-Quaternary bedrock on basin margins.

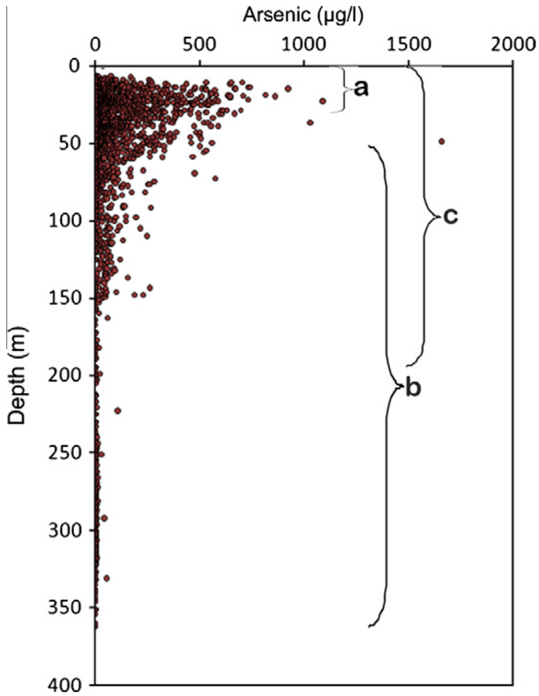

Fig. 3. Vertical distribution of As concentration in groundwater (BGS/DPHE, 2001) and depth ranges of low-As groundwater environments: (a) shallow groundwater beneath surficial sands in Recent and Holocene sediments, (b) deep groundwater in pre-Holocene sediments buried beneath the Holocene–Recent floodplains, (c) groundwater of the Plio-Pleistocene inliers.

Shamsudduha et al., 2009b) demonstrate that As concentration is elevated where the topographic slope is low and the water table is close to the surface. Recharge-induced flushing has been proposed to explain low-As concentrations at shallow depths beneath sandy surficial sediments (Stute et al., 2007; Aziz et al., 2008; van Geen et al., 2008; Weinman et al., 2008; Hoque et al., 2009).

Deep low-As groundwater is also widely present. In a national survey in Bangladesh (BGS/DPHE, 2001), of wells deeper than 150 m, fewer than 1% exceeded 50 µg/L and 95% had less than 10 µg/L As. Arsenic concentration is generally no more than a few µg/L at depths greater than 200 m. Low-As groundwater is found in oxidised 'red-bed' sediments at all depths (McArthur et al., 2004; von Brömssen et al., 2007) and has been associated with oxidised sands underlying paleosol horizons related to the Last Glacial Maximum (McArthur et al., 2008). Arsenic is below the WHO guideline concentration (10 µg/L) throughout the Plio-Pleistocene sediments of the Madhupur and Barind Tracts, and within their adjacent buried equivalents (BGS/DPHE, 2001), where low-As groundwater conditions persist to depths of at least 250 m (Burgess et al., 2010). The oxidation of the Pleistocene sediments has been linked to periods of sustained weathering during eustatic sea-level low stands from the Early Pleistocene. Low-As conditions also occur in grey, reduced Pleistocene sediments at depth in the south of the basin (Lowers et al., 2007). Sedimentologically equivalent grey sediments occur less commonly at depth beneath the Pleistocene tracts (Hoque, 2010). The Pleistocene sediments buried beneath the Holocene–Recent floodplains in the south of the basin therefore host low-As groundwater environments that have been related to a variety of conditions: oxidised sediments with a capacity for As sorption (McArthur et al., 2004; von Brömssen et al., 2007); the proposed diagenetic incorporation of As in pyrite in the more extensive deeply buried reduced sediments (Breit et al., 2006; Lowers et al., 2007); the refractory nature of sedimentary organic matter at depth (McArthur et al., 2004); and/or to the groundwater flow pattern (Michael and Voss, 2009a; Hoque, 2010) and history of groundwater flushing (DPHE/BGS/MML, 1999; McArthur et al., 2004).

The low-As groundwater environments may, therefore, be classified within the component parts of the BAS hydrogeological framework (Figs. 2, 4 and 5):

1. Throughout coarse-grained Holocene sediments in northerly regions where the topographic gradient is relatively pronounced.
2. At shallow depth (ca. 30 m) beneath surficial sands in Recent and Holocene sediments throughout the basin.
3. At all depths beneath the outcrop and shallow sub-crop of oxidised Plio-Pleistocene sediments.

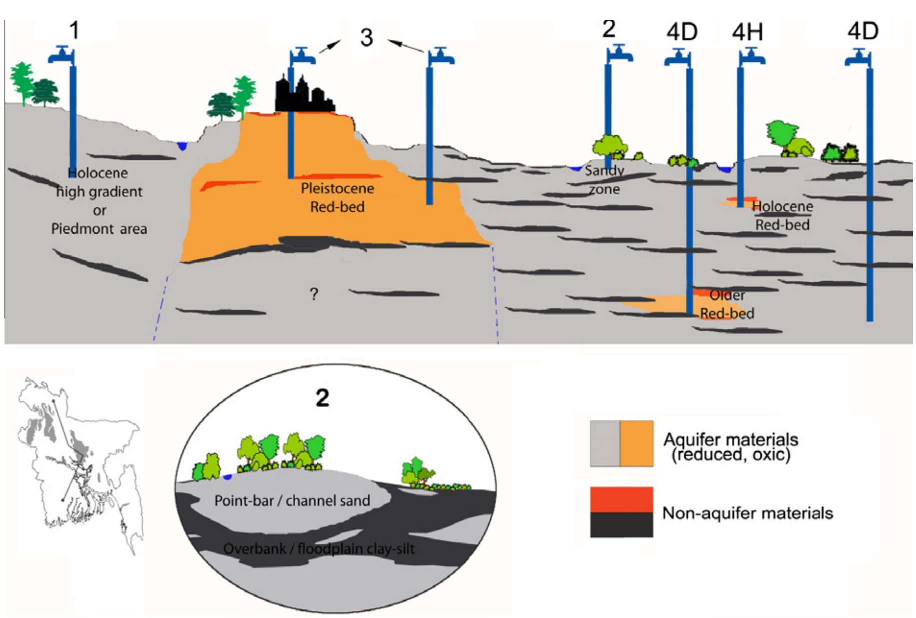

Fig. 4. Schematic illustration of the low-As groundwater environments (numerical system consistent with Fig. 2). 1, 2 and 4H are within Holocene sediments; 3 represents the Plio-Pleistocene inliers; 4D represents deeply buried Pleistocene sediments (both oxidised and reduced sediment types). Note environment '5' has not been shown.

4. In the buried sediments of the aquifer system, within (<100 m) and beneath Holocene sediments (>150 m) in the south of the basin, and at greater depths in the Sylhet sub-basin and coastal regions.
5. In the pre-Quaternary 'bedrock' around the margins of the basin.

It is proposed that the estimation of the boundaries of the host hydrogeological contexts enables preliminary delineation to be made of low-As groundwater within the BAS. The delineation is presented with reference to two depth ranges (shallow [<30 m] and deeper [>100 m]) and one geochemical indicator, 'red-bed' occurrence, which can be present in either depth range. Red-beds may have patchy to more extensive occurrence at any depth on account of the geological evolution of the basin (see Section 2). Therefore, the five low-As groundwater environments identified above (Fig. 4) are arranged into three groups:

- Shallow low-As groundwater of the Holocene floodplains.
- Low-As groundwater in oxidised 'red-bed' sediments at a variety of depths.
- Deep low-As groundwater.

4. A preliminary delineation of low-arsenic groundwater environments in BAS

The Pliocene–Holocene geological development of the Bengal Basin and the hydrogeological structure of the BAS have together provided the basis for identifying a variety of low-As groundwater environments. The preliminary delineation given in Fig. 6 is drawn

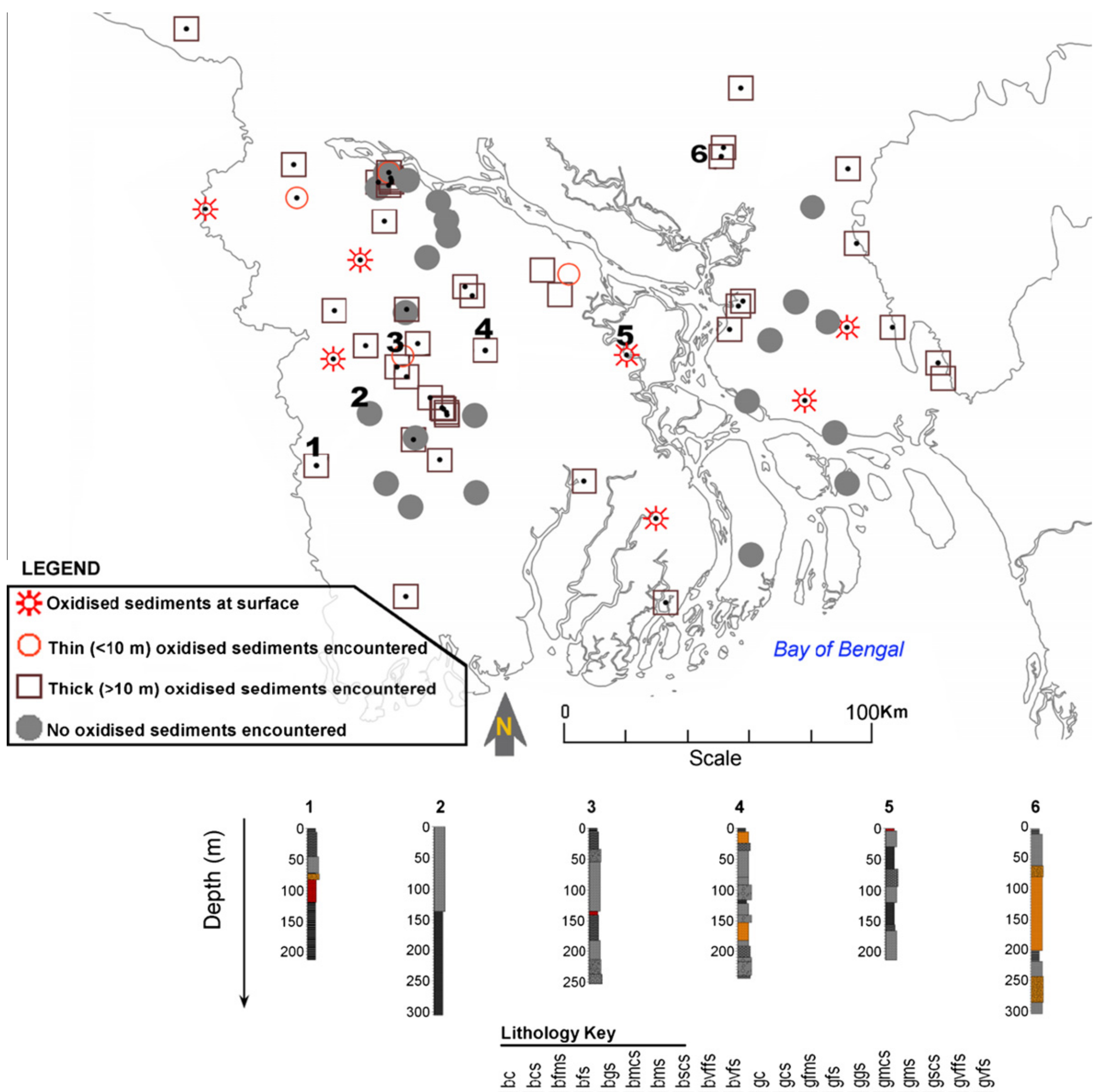

Fig. 5. Sediment colour (hence redox condition) distribution in southern Bangladesh. Lithological code prescript 'b' indicates yellowish-brown, i.e., oxidised sediments; prescript 'g' indicates grey, i.e., reduced sediments. 'c' = clay, 'scs' = silt–sandy clay, 'vfs' = very fine sand, 'vffs' = very fine to fine sand, 'fms' = fine to medium sand, 'ms' = medium sand, 'mcs' = medium to coarse sand, 'cs' = coarse sand, 'gs' = sand with gravel. Where symbols contain a centrally placed black dot, oxidised sediments are encountered at <100 m depth. Note that oxidised horizons occur at depth within predominantly reduced sequences in places (1, 4) and reduced horizons occur at depth within predominantly oxidised sequences of the Pleistocene inliers (6). Lithological logs compiled from Department of Public Health Engineering (DPHE), Bangladesh Water Development Board (BWDB), University of Dhaka (DU), Bangladesh University of Engineering and Technology (BUET), Local Government Engineering Department (LGED), Bangladesh Agricultural Development Corporation (BADC), and Dhaka Water Supply and Sewerage Authority (DWASA) (pers. comm.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from empirical associations of low-As groundwater with topography, water table elevation, surface sediment lithology, geology and the screen depth of deep wells in low-As zones.

4.1. Shallow low-As groundwater of the Holocene floodplains

The indicators used for delineating the regions of shallow low-As groundwater of the Holocene floodplains are: the presence of a shallow water table ($\geqslant$1 m to $\leqslant$7 m depth), the surface soil composition ($\geqslant$50% of loamy silt), and a restricted thickness of uppermost silty-clay (<15 m).

The proposed recharge-induced flushing of As beneath sandy surficial sediments of the Holocene floodplain provides the conceptual basis for estimating the depth limit of the shallow low-As groundwater environment as 30 m. Recharge penetrates to a depth (δ) approximated by Zijl (1999) from the scale of topographical undulation and the anisotropy of sediment hydraulic conductivity:

$$\delta = \lambda\sqrt{K_v/K_h}$$

where λ is wave length of a sinusoidal topography and K_v, K_h are, respectively, the vertical and horizontal hydraulic conductivity of the shallow sediments. In the fluvio-deltaic terrain of the Bengal Basin, topography is provided by slight elevation of sandy point bars generated by migrating river channels, approximately 100 m in lateral dimension. Taking the anisotropy in hydraulic conductivity, K_h/K_v, for sand bars as 10 (Freeze and Cherry, 1979), the depth of the recharge-induced flushing effect is estimated at approximately 30 m.

A very shallow water table ($\leqslant$1 m) correlates with elevated As (Ravenscroft et al., 2005; Shamsudduha et al., 2009b). The area meeting the criterion was identified at >1 m depth from the national-scale map of the depth to the water table (454 monitoring points across Bangladesh; Shamsudduha et al., 2009a). The MPO (1987) map (derived from 17,764 drillers' logs), was used to determine where surface silty-clay is <15 m thick, facilitating recharge to the aquifer. Soil composition also facilitates recharge (Aziz et al., 2008). Surface soil composition data (BARC, 1988) was collated and areas identified where surface soil contains $\geqslant$50% loamy silt.

Multi-parameter spatial modelling of these indicators in a geographic information system has been used to delineate the extent of the shallow low-As groundwater environments in the Holocene floodplains. The spatial limits of the shallow low-As groundwater were delineated (Fig. 6) by modelling of areas in ArcGIS 9.2 (http://www.esri.com) giving agreement for $A \cap B \cap C$, where 'A' denotes surface soil containing $\geqslant$50% loamy silt, 'B' for the water table which is $\geqslant$1 m and $\leqslant$7 m depth below ground surface, and 'C' indicates areas where surface silty-clay is <15 m thick. The suction limit of hand-pumped tube-wells (HTW) is 7 m and hence this criterion omits regions where shallow groundwater cannot be exploited by HTW.

This spatial modelling output includes some areas of the Plio-Pleistocene tracts, which host As-low groundwater because of their 'red-bed' nature (Section 3). These tracts have separately been delineated according to the mapped geological boundaries (Alam et al., 1990) and they have been excluded from the 'shallow low-As groundwater of the Holocene floodplains' group. The regions delineated in this manner should encompass the shallow low-As groundwater environments of the Holocene floodplains in Bangladesh, situated beneath land of slight elevation which remains above the seasonal surface flood-level.

4.2. Low-As groundwater in oxidised 'red-bed' sediments at variety of depths

The low-As groundwater environment associated with the Plio-Pleistocene inliers (the Madhupur and Barind tracts) at all depths to at least 250 m, and from very shallow depth around the margins of their outcrops, has been delineated (Fig. 6) on the basis of the geological map of Bangladesh (Alam et al., 1990).

Delineation of the buried, sub-Holocene oxidised sediments is complicated by uncertainties associated with their partial preservation, potentially in multiple horizons, within the thick Pleistocene sequence lying below about 150 m depth throughout the southern part of the basin. Compilation of 80 lithological logs with information on sediment colour from southern Bangladesh (LGED, DPHE, and BWDB, pers. comm.) indicates regions of frequent but discontinuous 'red-beds' in SW Bangladesh (Fig. 5) with no consistent depth of occurrence. An empirical basis for delineating this environment as 'deep low-As groundwater', consistent with its situation within the BAS, is described below.

4.3. Deep low-As groundwater

The depth-limited distribution of As (Fig. 3) has provided the incentive for use (Bhattacharya et al., 1997) of deep groundwater as the principal source of low-As water supply throughout southern Bangladesh (Ahmad et al., 2006; Johnston and Sarker, 2007; Opar et al., 2007; Johnston et al., 2010). There is, however, no uniformly suitable and accepted depth for setting a well screen to access deep low-As groundwater, because at intermediate depth the thickness of overlying low permeability layers is variable, where present (Burgess et al., 2010; Hoque, 2010) and brackish groundwater is frequently encountered in coastal regions (Ravenscroft and McArthur, 2004; Burgess et al., 2010). However, the majority of the deep wells targeting deep low-As groundwater in the BAS are at >150 m depth (van Geen et al., 2002, 2003a; Ahmed et al., 2006). More than 75,000 deep hand-pumped wells had been installed in Bangladesh by 2007 (Ravenscroft et al., 2009); the vast majority of these wells comply with the regulatory guidelines for As and salinity (DPHE/DFID/JICA, 2006). Deep groundwater also provides the water supply for more than 20 provincial towns and more than 100 rural supply schemes (Burgess et al., 2010).

The screen depth of these existing wells can be used as an empirical guide to delineate the deep low-As groundwater environment of southern Bangladesh. Data for the 1380 deep wells of southern Bangladesh (DPHE/DFID/JICA, 2006) for which quality-controlled As data were available have been collated. The analysis suggests that the depth of the low-As groundwater increases southward from <150 m to >300 m (Fig. 6). A basin-scale compilation of quality-controlled As data from deep (>150 m) wells (Burgess et al., 2010) has indicated regions, aligned with paleo-channels on the western and eastern margins of the basin (Hoque, 2010), within which groundwater As is elevated in some cases (18% at >10 μg/L, <2% at >50 μg/L). The significance of these apparent anomalies is discussed below.

5. Discussion

The maps presented in Fig. 6 indicate regions where low-As groundwater can be expected and might be sought, but do not imply the absence of groundwater As, nor that sustained development of low-As groundwater in these regions would be secure against As invasion. Sustainability of the groundwater resources is not implied, though security against As at any well is critical to its safe use over a prolonged duration. This caveat applies especially to environment 2 (shallow depth beneath surficial sands in Recent and Holocene sediments throughout the basin) and 4 (at depth in the aquifer system, within (<100 m depth) and beneath Holocene sediments (>150 m depth) in the south of the basin and at greater depths in the Sylhet sub-basin and coastal regions).

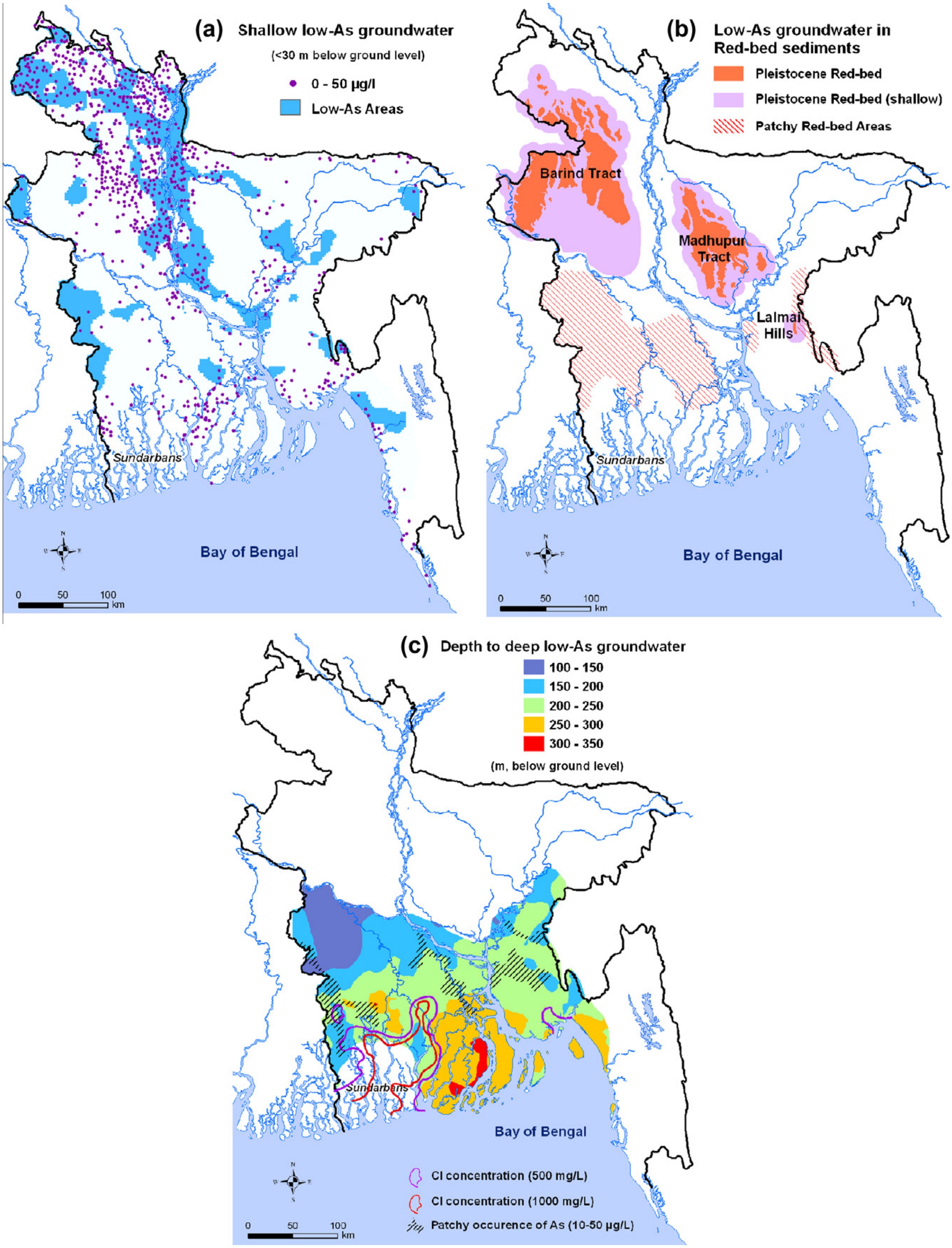

Fig. 6. A preliminary delineation of the low-As groundwater environments of Bangladesh. (a) Shallow low-As groundwater of the Holocene floodplains; (b) low-As groundwater in oxidised 'red-bed' sediments; (c) deep low-As groundwater, patterns of occurrence of As at 10–50 μg/L, and the extent of high-Cl^- groundwater are indicated as a precaution. For details see text.

Programmes of testing and monitoring groundwater As are essential, especially in these environments.

A large-scale As-testing programme in the Araihazar area of Narayanganj district, Bangladesh, led to identification of low-As wells with the intention of supporting a well-switching programme (van Geen et al., 2002). Short term (3-year) monitoring (Cheng et al., 2005; Dhar et al., 2008) in shallow wells in the same location, representing the low-As environments 2 and 3 (Section 3), indicated no consistent change of groundwater As concentration, despite an intriguing and as-yet-unexplained possibility that low-As wells had a decreasing trend and high-As wells had an increasing trend (Hoque, 2010).

Modelling studies of representative shallow hand-pumped tube-well catchments (Cuthbert et al., 2002; Burgess et al., 2007) without topography conclude that hand-pumped wells in the shallow low-As groundwater environment may generally experience an increasing trend in As concentration over one to several decades. Shallow groundwater flow is significantly modified by high-yielding irrigation abstraction (Harvey et al., 2002), and the effect could be to enhance As contamination of shallow wells (Cuthbert et al., 2002), which are known to be vulnerable to microbial (*Escherichia coli*) contamination (Leber et al., 2010).

The security of deep low-As groundwater environments against invasion by As, as a consequence of pumping, relies both on the hydraulic and the geochemical context (Burgess et al., 2010). Michael and Voss (2008, 2009a) have recommended a cautious development of the deep low-As groundwater resource by hand-pumped wells only. Basin-scale groundwater flow modelling suggests that, over large parts of the deep low-As groundwater environments, deep hand-pumped wells may be secure against As invasion for hundreds of years, but widespread deep irrigation pumping might lead to degradation of the low-As groundwater within decades (Michael and Voss, 2008). Certainly, monitoring of the groundwater As concentration in the deep wells is recommended because of the potential of As breakthrough from shallow levels. Some deep wells in south-central Bangladesh are known to have anomalous elevated As (DPHE/DFID/JICA, 2006; Burgess et al., 2010), but these are located in a sub-region which stands out as more vulnerable to vertical flow on account of basin geometry (Michael and Voss, 2008) and it is unclear that they represent a hydrological response to pumping.

Low-As groundwater in oxidised 'red-bed' sediments is more secure against As invasion than groundwater in reducing sediments, on account of the geochemical defence (Burgess et al., 2010) provided by the sorption capacity of the red-bed sediments (Stollenwerk et al., 2007). The effect of setting a well screen 10 m into oxidised sediments could be to protect the well against inward migration of As by over 4000 years (Stollenwerk et al., 2007; Radloff et al., 2010). However, except at the outcrops of the oxidised Plio-Pleistocene inliers, mapping of individual occurrences of red-bed sediment is not possible. Our delineation indicates where they can be expected and might be sought. At specific locations, existing lithological logs with colour information should be sought to guide the search for low-As groundwater in this environment, and careful examination of the grain size and colour of drill-cuttings should be made.

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