Palaeosol Control of Arsenic Pollution: The Bengal Basin in West Bengal, India

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Abstract

Groundwater in the Bengal Basin is badly polluted by arsenic (As) which adversely affects human health. To provide low-As groundwater for As mitigation, it was sought across 235 km^2 of central West Bengal, in the western part of the basin. By drilling 76 boreholes and chemical analysis of 535 water wells, groundwater with <10 µg/L As in shallow aquifers was found under one-third of a study area. The groundwater is in late Pleistocene palaeo-interfluvial aquifers of weathered brown sand that are capped by a palaeosol of red clay. The aquifers form two N-S trending lineaments that are bounded on the east by an As-polluted deep palaeo-channel aquifer and separated by a shallower palaeo-channel aquifer. The depth to the top of the palaeo-interfluvial aquifers is mostly between 35 and 38 m below ground level (mbgl). The palaeo-interfluvial aquifers are overlain by shallow palaeo-channel aquifers of gray sand in which groundwater is usually As-polluted. The palaeosol now protects the palaeo-interfluvial aquifers from downward migration of As-polluted groundwater in overlying shallow palaeo-channel aquifers.

The depth to the palaeo-interfluvial aquifers of 35 to 38 mbgl makes the cost of their exploitation affordable to most of the rural poor of West Bengal, who can install a well cheaply to depths up to 60 mbgl. The protection against pollution afforded by the palaeosol means that the palaeo-interfluvial aquifers will provide a long-term source of low-As groundwater to mitigate As pollution of groundwater in the shallower, heavily used, palaeo-channel aquifers. This option for mitigation is cheap to employ and instantly available.

Introduction

The World Health Organization's guideline value for arsenic (As) in drinking water is 10 µg/L (WHO 2011). Some 25% of water wells tapping the shallow aquifers of the Bengal Basin (West Bengal and Bangladesh) contain more than 10 µg/L As (PHED 1991; DPHE 1999; van Geen et al. 2003a; Jakariya et al. 2007; Nickson et al. 2007). As a consequence, some 78 million consumers (Chakraborti et al. 2009; BBS/UNICEF 2011) are at risk of adverse effects on their health (Chatterjee et al. 1995; Smith et al. 2000; Chakraborty et al. 2002; Yu et al. 2003). As many as 22% of those consumers may die as a result of As-related disease (Argos et al. 2010).

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In DPHE (1999), it was shown that As pollution in the Bengal Basin is confined largely to groundwater in shallow sands deposited since the last glacial maximum (LGM), as sea level rose after its termination around 20 ka. These post-LGM sands were laid down on a late Pleistocene landscape that had formed during the eustatic fall of sea level between 125 and 20 ka (Umitsu 1993; Davies 1995; DPHE 1999; Goodbred and Kuehl 2000a, 2000b). In DPHE (1999), it was also shown that concentrations of As were usually much less than 10 µg/L in the groundwater in pre-LGM sands that underlay the now-buried late Pleistocene land surface. These early observations have been repeatedly confirmed (DPHE 2001; van Geen et al. 2003a; McArthur et al. 2004; Zheng et al. 2005 et seq). One option for As mitigation is therefore to shift abstraction of groundwater for domestic supply away from the shallow, post-LGM, aquifers and into the deeper, pre-LGM, aquifers (DPHE 1999, 2001; van Geen et al. 2003b; Ahmed et al. 2005; Zheng et al. 2005; Ravenscroft et al. 2009; Mosler et al. 2010; Ravenscroft et al. 2013).

Where the late Pleistocene landscape crops out, that is, around the basin margin and in the upstanding blocks of the Barind and Madhupur Tracts, the pre-LGM aquifers are much exploited. Away from those areas, where the late Pleistocene land surface is buried, their exploitation by private owners is uncommon. One

reason for that under-exploitation is that private wells are usually installed in the first aquifer encountered during drilling and drilling deeper costs more. The first aquifer encountered is usually the As-polluted, post-LGM aquifer. Even today, ignorance of its pollution is widespread.

Another reason for under-exploitation of the pre-LGM aquifers is a lack of knowledge about where and at what depth they can be found. As a consequence, to ensure a well screen is emplaced in a pre-LGM aquifer, the top of the screen needs to be somewhat deeper than 120 m, the sea-level lowering at the peak of the LGM. Such depths of installation are too costly for the rural poor, for whom the maximum is 60 m in West Bengal, where iron pipe is used to drill for well-installation, and 90 m in Bangladesh, where lighter plastic pipe is used to drill.

The sedimentological models of Umitsu (1993) and Goodbred and Kuehl (2000a, 2000b) for the evolution of the Bengal Basin over the last glacial cycle imply that the depth to the top of the palaeo-interfluves of the late Pleistocene land surface may be no more than 45 mbgl over much of the basin. Those authors also noted that the LGM land surface was capped by a lateritic clay soil, leading to the prediction by McArthur et al. (2008) that this clay palaeosol should protect palaeo-interfluvial aquifers from downward movement of As-polluted groundwater in overlying, post-LGM aquifers and so ensure their long-term delivery of low-As groundwater.

The possibility that these pre-LGM aquifers may be widespread and accessible for As mitigation is a hypothesis that needs to be tested. The effectiveness, and prevalence, of the protection afforded them by the LGM palaeosol, or equivalent aquicludes, from downward migration of As pollution from overlying aquifers is also in need of quantification. If they are widespread and well-protected, their exploitation could provide a viable way to mitigate As pollution of groundwater. In order to further this task, palaeo-interfluvial aquifers *and their capping LGM palaeosol* were searched for across 235 km^2 of central West Bengal, in the western Bengal Basin. The findings are reported here. Finally, using data from Dasdia, the most intensely sampled part of our field area, the effectiveness is shown of the LGM palaeosol as a barrier to the downward movement of As pollution.

Hydrogeologic Background

Development of the Bengal Basin

Summarizing the models of Umitsu (1993) and Goodbred and Kuehl (2000a, 2000b), in the period from 125 to 20 ka, sea level fell around −120 m as compared with today. In the Bengal Basin, the shore-line retreated southward by 100 km and the areas exposed were eroded to create a late Pleistocene landscape of river channels and interfluves, all at an elevation lower than that of today's land surface (Umitsu 1993; Davies 1995; DPHE 1999, 2001; Goodbred and Kuehl 1999, 2000a, 2000b); Allison et al. 2003; Goodbred et al. 2003; Goodbred 2003; Pate et al. 2009).

The maximum depth of river incision at the LGM would have been little more than −120 m in relation to today's ground level. This depth would have been reached only at the LGM shoreline. Inland, in the region of the present subaerial delta, the depth of incision would have been less, with a maximum of around 90 m being likely (Goodbred and Kuehl 2000a).

The long period of weathering between 125 and 20 ka allowed a soil of red clay to develop on the interfluves. This unit is the laterite of Goodbred and Kuehl (2000a), and was also termed the LGM palaeosol or LGMP by McArthur et al. (2008). The interfluvial sands beneath this soil were also weathered and oxidized (Davies 1995; DPHE 1999; Goodbred and Kuehl 2000a, 2000b). These oxidized brown sands and the capping palaeosol were termed the "oxidized facies" by Goodbred and Kuehl (2000a). The brown sands of the oxidized facies are typically less than 30 m in thickness and pass downward into pre-LGM gray sands (Goodbred and Kuehl 2000a; Hoque et al. 2014).

When sea level rose to about its present level during the interval 18 to 6 ka, the late Pleistocene landscape was gradually submerged and the accommodation space created first allowed the river valleys to fill with post-LGM gray sands. When sea level overtopped the interfluves, silts and muds were deposited on their distal regions. From around 6 ka, when sea level reached its present level, delta progradation allowed development of mangroves and peatlands. River avulsion since 6 ka has left a patchwork of fluvial sands across much of the basin. The buried features of this late Pleistocene landscape are termed palaeo-channels (PCs) and palaeo-interfluves (PIs) hereinafter.

Hydrostratigraphy

The sedimentological development of the Bengal Basin has given rise to four common settings for its aquifers. These are summarized in Figure 1 in a simplified generic model of aquifer distribution. It is the validity of this generic model that is tested here.

The ancient river-valley fills of gray sand now comprise the deep palaeo-channel (DPC) aquifers of the basin. The shallower areas, typically < 30 m deep, that have been reworked by river avulsion since 6 ka now constitute the shallow palaeo-channel (SPC) aquifers of the basin (Hoque et al. 2014).

The sands beneath the LGM surface comprise the pre-LGM aquifers. They are termed palaeo-interfluvial, or PI, aquifers hereinafter. They are usually capped by the LGMP. The oxidized upper parts of the PI aquifers are termed "brown sands" (DPHE 1999; Harvey et al. 2002; Zheng et al. 2005; von Brömssen et al. 2007, 2008; Biswas et al. 2014). Where preserved today, the LGMP has been shown by pump testing (McArthur et al. 2004) to form an effectively impermeable barrier to groundwater flow. The LGMP prevents groundwater in post-LGM, PC aquifers from migrating downward into the pre-LGM PI aquifers. Beneath the oxidized sands of the PI aquifers and beneath the LGM palaeo-channels, oxidation was
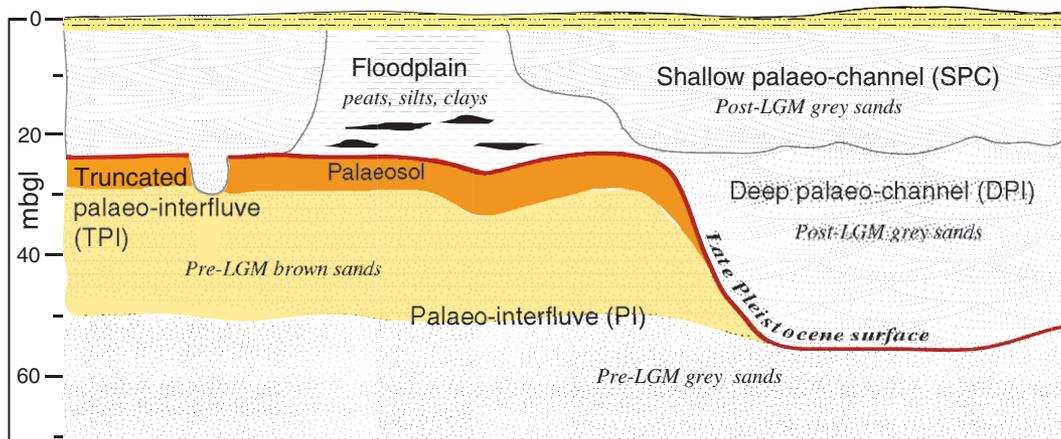
Figure 1. Schematic of the main aquifer types in the Bengal Basin. See text for explanation.

limited, and the pre-LGM sands are gray to indeterminate depth.

Water Quality and Aquifer Type

The groundwater in gray PC, and in brown PI, aquifers differ chemically (Davies 1995; DPHE 1999, 2001; van Geen et al 2003a, 2003b; Zheng et al. 2005; von Brömssen et al. 2007, 2008 et seq). The PC aquifers typically host groundwater that contains >10 µg/L of As, >0.9 mg/L of Fe, <0.2 mg/L Mn, and Mo in the low ppb range. Groundwater from the weathered, brown, PI aquifers typically contains <5 µg/L of As, <0.9 mg/L of Fe, >0.2 mg/L Mn, and V and U in the low ppb range (Hoque et al. 2012, 2014; McArthur et al. 2012a). Explicit comparison of the composition of groundwater from either aquifer with that of groundwater from gray, pre-LGM sands is lacking, excepting that groundwater in the pre-LGM gray sands contain mostly <10 µg/L As (DPHE 1999, 2001; Hug et al. 2011; Ravenscroft et al. 2013).

Field Area

The study area comprises 235 km^2 of the Bengal Basin in West Bengal between latitudes 22.9 and 23.1°N and longitudes 88.5 to 88.7°E. The study area is part of the Jamuna subbasin that comprises 1500 km^2 of the surrounding area (Figure 2). The area encompasses 22 villages of Haringhata Block, in the administrative division of Nadia district, and 2 villages in Gaighata Block in the administrative division of North 24 Parganas (Figure 2). The Jamuna River runs across the area, joining the River Hugli in the west to the River Ichamati in the east. The Jamuna River is ponded and flow is rare and seldom deeper than 1.5 m. The climate of the area is monsoonal, receiving around 1450 mm per year of rainfall, 80% of which falls between June and October.

Methods

To investigate the subsurface lithology, 76 boreholes were drilled and chemical analysis of 535 well waters was performed. Well locations were recorded by handheld GPS, referenced to the WGS 84 coordinate system. Drilling and well-sampling were guided by a survey of 1547 wells for the color of stain left by well water on completions and domestic utensils: low-As groundwater from PI aquifers contains Mn and stains black and As-polluted groundwater from PC aquifers contains Fe and stains red (McArthur et al. 2011).

For 73 boreholes up to 45 m depth, the hand-operated reverse-circulation method was used (Ali 2003). For three holes drilled to 122 mbgl, rotary drilling was used. Cuttings were collected at 1.5 m intervals and logged, photographed, and sampled.

Sampled wells were <70 m deep. Samples were taken after purging into two 15 mL polythene tubes, one acidified in the field with 0.15 mL of 50% Analar® nitric acid for cation analysis, one unacidified for anion analysis. Samples were filtered using 0.45-µm membrane filters only when visibly turbid because filtered and unfiltered compositions are indistinguishable unless samples are turbid (e.g., Zheng et al. 2004). Chemical analysis for Fe and Mn was performed by ICP-AES using matrix-matched standards, for As, Mo, V, and U by ICP-MS using matrix-matched standards, and for Cl, NO$_3$, and SO4 by ion chromatography.

Results

Drilling

A summary of the drilling information is given in Table S1 of the Supporting Information including well locations. In Figure 3 shown are typical representations of lithological logs of samples, recovered by drilling, which are representative of the main sedimentological settings shown in Figure 1.

Across the area, the surficial cover comprises an upper aquitard of light brown clay, silty clay, or sandy silt. The thickness of this cover is typically 3 to 6 m, but exceptions occur. For example, at Bamanberia (BB5) and Mollabelia (MB2), fine sand extends to the surface.
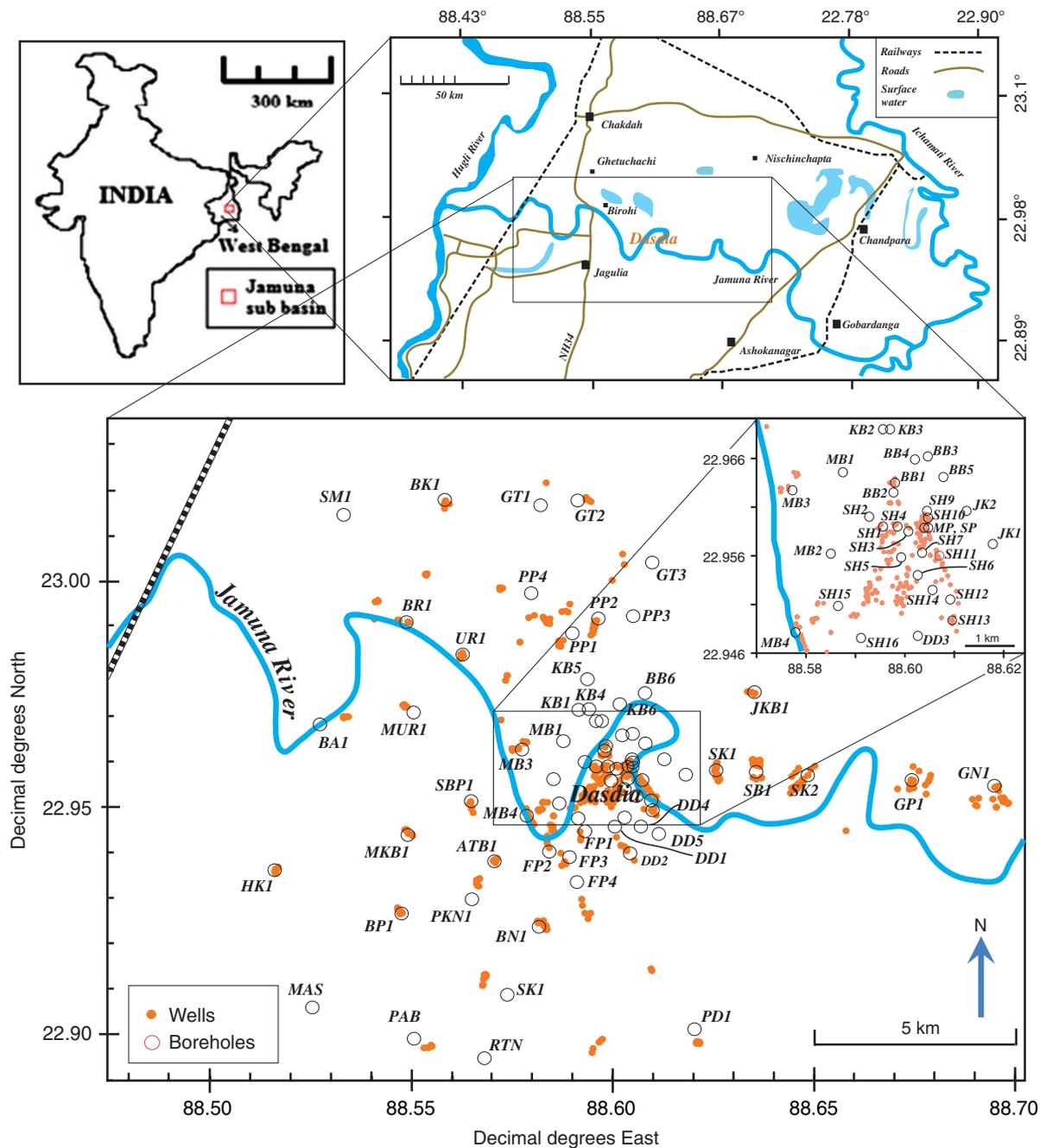
Figure 2. Location in the field area in central West Bengal of sampled wells (filled circles) and boreholes drilled for this study (open circles). The area lies within the Jamuna subbasin of West Bengal (upper inset).

Beneath this surficial upper aquitard, four sedimentary sequences are recognized on the basis of the occurrence of, and depth to, brown sands and gray sands; the presence or absence of the LGMP; and the stratigraphic order of these lithologies. The sequences recognized are as follows:

1. *Palaeo-channel, GP1*. Figure 3a. Gray sands to the depth drilled, with clay intercalations, here at 23 m (75 feet). For reasons given in the text, the upper 35 m (115 feet) of sand is termed the *shallow palaeo-channel* (SPC) aquifer and deeper sand is termed the *deep palaeo-channel* aquifer (DPC) aquifer.

2. *Palaeo-interfluve under SPC, MB4*. Figure 3b. Brown sands are overlain by the LGMP, here between 29 m (95 feet) and 35 m (115 feet). Together, these units comprise the *palaeo-interfluvial* (PI) sequence. The LGMP is overlain by 1.5 (5 feet) of pale blue-gray clay and 1.5 m of dark brown clay. An SPC aquifer of gray sand between 9 and 26 m (30 to 85 feet) overlies the clays.

3. *Palaeo-interfluve under floodplain clays, GT1*. Figure 3c. Silty clays overlie a palaeo-interfluvial sequence of LGMP over brown sand. The LGMP in this core lies between 27 and 34 m (90 and 110 feet).
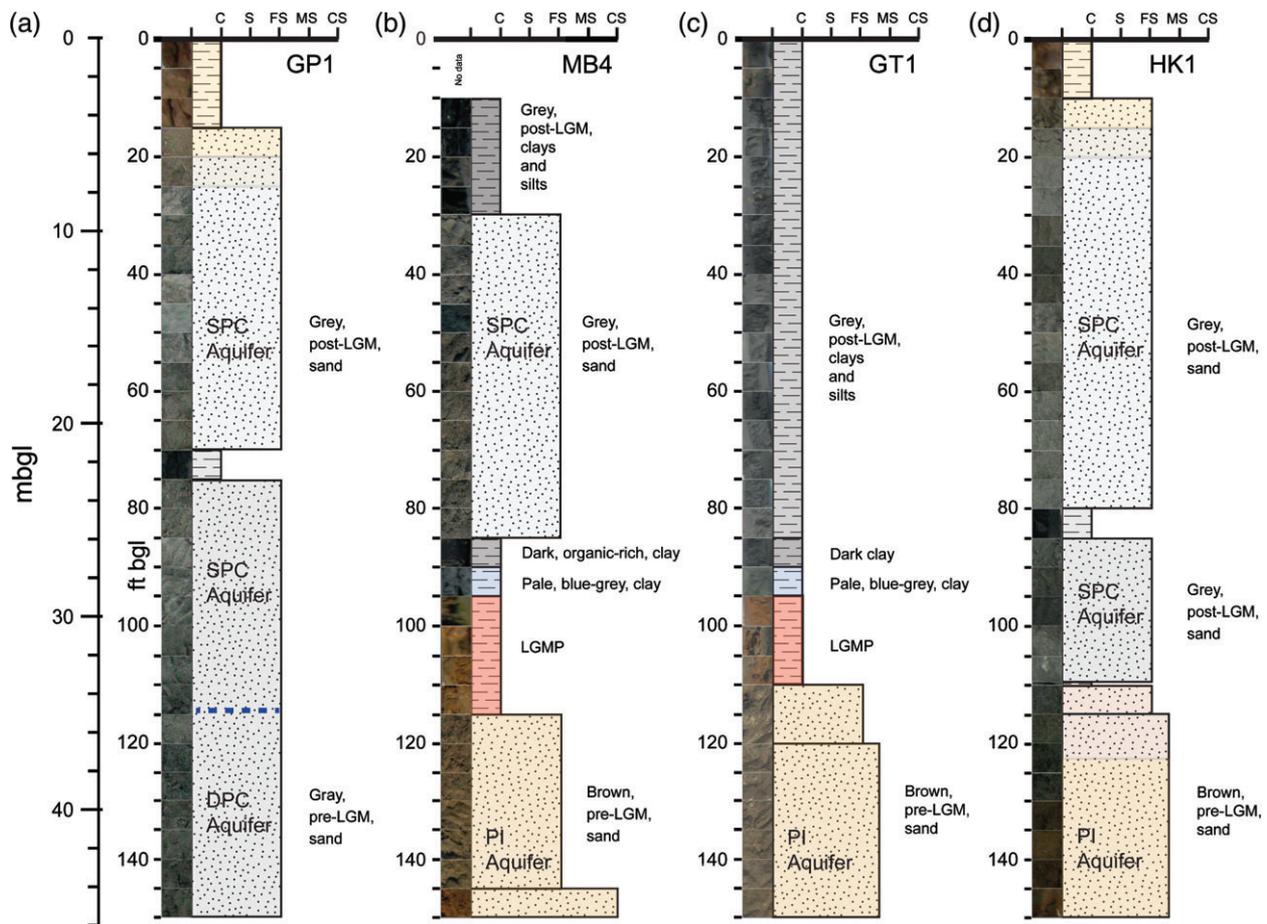
Figure 3. Sedimentary sequences recovered in drilling; details in Table S1. Depths are relative to ground level. See text for explanations. (a) *Shallow and deep palaeo-channels*, **GP1**. For reasons given in the text, the upper 35 m (115 feet) of sand is termed the SPC aquifer and deeper sand is termed the DPC aquifer. **(b)** *Palaeo-interfluve under SPC, MB4*. The upper 3 m (10 feet) were absent as the borehole was sited at −3.0 m elevation in the bed of the Jamuna River. **(c)** *Palaeo-interfluve under floodplain clays, GT1*. **(d)** *Truncated palaeo-interfluve under SPC, HK1*.

4. *Truncated palaeo-interfluve under SPC, HK1*. Figure 3d. Gray sands of the SPC sequence pass downward into brown sands of a PI sequence. River incision has removed the LGMP but not the underlying PI brown sand, the top of which lies at 34 m (110 feet) in that borehole.

Occasional departures from this classification were observed. At MKB1, SKP1, and RTN (Table S1), red clay extends from the top of the LGMP to the base of the hole, although local knowledge and the existence of nearby wells attest to these thicknesses being very local phenomena. At Baksha (Sonakhali), the LGMP is present but is underlain by gray sands, a rare occurrence noted only at palaeo-interfluvial margins.

Groundwater Composition

The results for laboratory analyses of well waters, the aquifer type as revealed by drilling and/or the color of well completions, and geographical locations of wells are given in Tables S1 and S2. Guided by drilling results, waters from wells 35 to 70 m deep from around each drilling site were classified as derived from either a DPC or a PI aquifer. Only wells in that depth range were used because drilling showed that brown sands of the PI aquifers were within that depth range. Away from drill sites, the known compositional differences between PI and PC groundwaters in West Bengal were used to identify the aquifer type in which the well was screened. For the DPC aquifers, limiting concentrations were >10 μg/L of As, >0.9 mg/L of Fe, and U and V <1 μg/L. For brown PI aquifers, they were <5 μg/L of As, <0.9 mg/L of Fe, and V and U >1 μg/L. Molybdenum and Mn were not useful in assigning aquifer type, in contrast to their value in this task further south in West Bengal (McArthur et al. 2011; Hoque et al. 2012). The impact on groundwater composition of waste water and, at PI margins, mixing of PI and PC groundwaters can make uncertain the assignment of aquifer type using water composition. Such mixed signals were too few in number to significantly influence our interpretations.

Aquifer Delineation

Combining drilling data with data on water composition for wells between 35 and 70 mbgl has allowed the subsurface distribution of the PI aquifers to be delineated
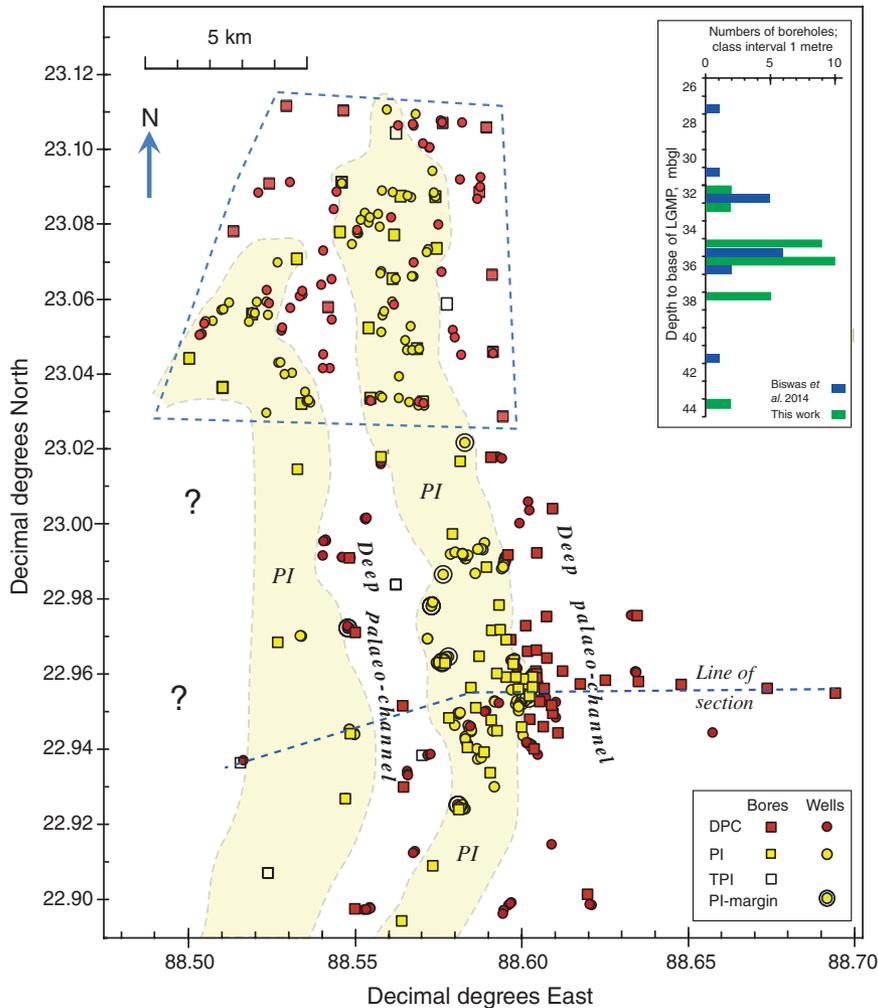
Figure 4. Spatial distribution of palaeo-interfluvial, and truncated palaeo-interfluvial, aquifers as defined by drilling, color mapping of wells, and composition of well water (see text for explanation). Borehole numbers in Figure 1. Dotted box encloses data of Biswas et al. (2014) for well waters and drill locations, and the PI distribution in that boxed area minimally modified from that predicted by Hoque et al. (2012). Blue hatched line is the line of the cross section shown in Figure 5.

across the region and that distribution is shown in Figure 4. A cross section through the study area from west to east is shown in Figure 5.

The DPC aquifer and PI aquifers form north-south lineaments through the area. The eastern half of the study area comprises a DPC. It is flanked on the west, between 88.51 and 88.60°E, by two linear, N-S trending palaeo-interfluves, each 2 to 4 km wide, between which lies a shallower palaeo-channel about 3 km wide where river incision through the LGMP has emplaced post-LGM gray sands directly onto pre-LGM brown sands (Figure 3d) or entirely eroded the latter, leaving DPC gray sands. The western extent of the western palaeo-interfluve is not well defined because of a lack of data.

Discussion

Implications for Mitigation

Our results delineate two PI aquifers across large parts of our study area (Figures 3 to 5). These aquifers

host groundwater containing ≤6 µg/L As. A further large area of PI, also hosting low-As groundwater, immediately to the north of our study area (Figure 4), was predicted to exist by Hoque et al. (2012). The prediction has recently been confirmed by drilling (Biswas et al. 2014), consequently the area thus delineated has been incorporated into Figure 4. The depth to the top of the PI aquifers in our area ranges mostly from 35 to 38 mbgl, with outliers of 32 and 44 mbgl (inset Figure 4; Table S1). In the region of study by Biswas et al. (2014), to the north of ours, the depth to top of the PI aquifers is mostly between 32 and 36 mbgl, with outliers of 27 and 41 mbgl (inset to Figure 5). The depth to the palaeo-interfluves thus decreases northward, as would be expected given equal post-LGM subsidence. In order for the PI aquifers underlying the LGMP to be exploited successfully for mitigation, the tops of screens must be emplaced in the PI sands *beneath the LGMP*, and preferably some meters below. With a drilling depth of 60 m attainable in West Bengal, and the typical screen length of 3.7 m (12 feet), the screen tops would be at 46 mbgl, which would be
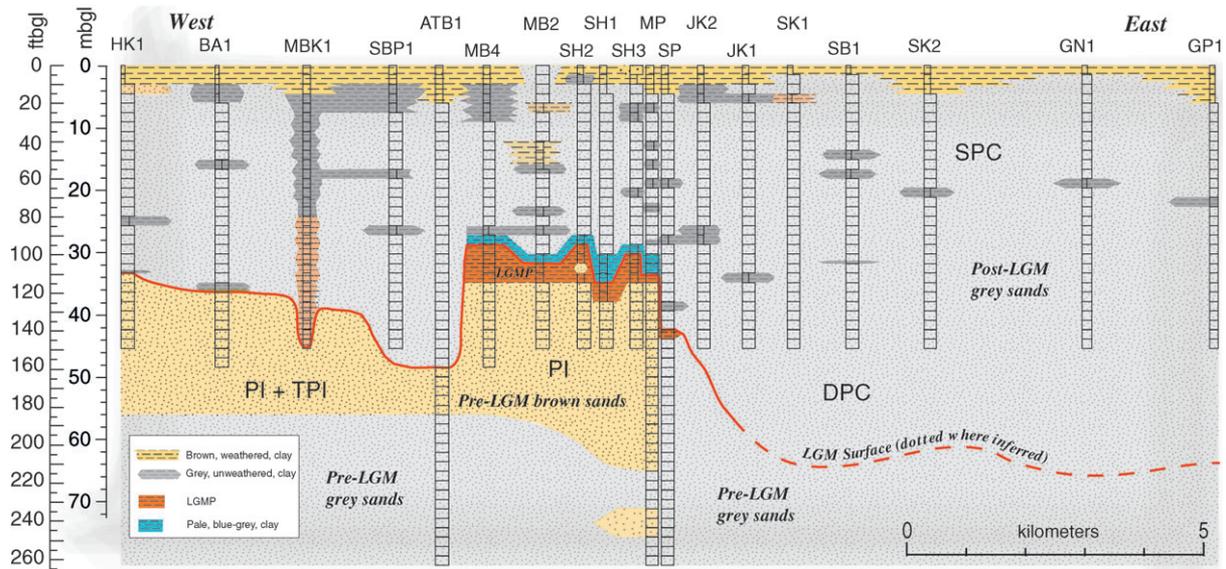
Figure 5. Sedimentary sequences across the study area showing palaeo-channel and palaeo-interfluvial zones along the line-of-section shown in Figure 4.

below the top of the PI aquifers in all localities in both areas.

The knowledge that a PI aquifer, that yields low-As groundwater, exists at an accessible depth *under the protective LGMP or other aquiclude* is simple to convey at village level. The ability to exploit that knowledge for mitigation exists in local communities among local drillers, who know the stratigraphy of their areas. What few drillers are aware of is the implication of that stratigraphy with respect to As pollution. Teaching them the implication of the stratigraphy would do more to mitigate As pollution across the Bengal Basin than most other mitigation strategies, and at a fraction of the cost.

Importance of the LGMP

Exploitation of aquifers of brown sand, now recognized as the upper part of PI aquifers, has been widely mooted as an As-mitigation strategy. The strategy is reliant on the sorptive capacity of the brown sands for As (DPHE 1999; Zheng et al. 2005; Stollenwerk et al. 2007; von Brömssen et al. 2007, 2008; McArthur et al. 2008; Biswas et al. 2014). Execution has been minimal. One reason for under-exploitation is that PI aquifers may be vulnerable to downward migration of As-polluted groundwater in overlying SPC aquifers (e.g., Stollenwerk et al. 2007) although local protection by intercalated clays has been noted (Swartz et al. 2004; Zheng et al. 2005).

The concern about downward invasion is real. The vertical thickness of the brown sands, that is, the oxidized part of PI aquifers, is typically only a few tens of meters. The sorption capacity of underlying gray sands is not known. Where SPC sands sit on PI brown sands, for example, at Moyna some 60 km south of the present study area (McArthur et al. 2008), groundwater moving downward creates a reduction front at which As is released. The front has burned 7 to 8 m downward into the brown

sands and the As released has migrated another 5 or some meters downward. Groundwater ages are 22 to >50 years (McArthur et al. 2010) and give an approximate timescale to the process. Local pumping has also drawn As pollution downward locally around individual wells which have become polluted over timescale of 2 to 10 years.

It is therefore unwise to assume brown sands will prevent *downward* migration of As into PI aquifers in the medium or long term, largely because of the limited thickness of the brown sands. The PI brown sands must be separated from any overlying SPC aquifer by an LGMP, or equivalently confining aquiclude, in order to ensure long-term sustainability of the low-As source. In the next section, the region of Dasdia, the region most heavily sampled for this work, is used to show the protection afforded to a PI aquifer that is separated by the LGMP from a directly overlying, As-polluted, SPC aquifer.

Protection Afforded by the LGMP

In Figure 6a shown is the distribution of As pollution in water from 122 wells in the village of Dasdia, in the center of our study area. Beneath the upper aquitard, the entire area shown in Figure 6a is underlain by an SPC aquifer at depths up to 38 mbgl. In the north east corner of Dasdia, the SPC sands sit directly on DPC sands (Figure 6b). Across the rest of Dasdia, the SPC aquifer is separated from an underlying PI aquifer by the LGMP (Figure 6c).

Across Dasdia, 38 wells tap the PI aquifer. The maximum concentration of As in these wells is 6 µg/L (Figure 6e; Table S2). The DPC aquifer, in Dasdia's extreme northeast, is tapped by six wells and five of them contain >60 µg/L of As. Another 77 wells across Dasdia tap the SPC aquifer; in the water from 60 wells, concentrations of As are >10 µg/L. Had those 60 SPC wells been drilled to a depth of more than 38 m in order
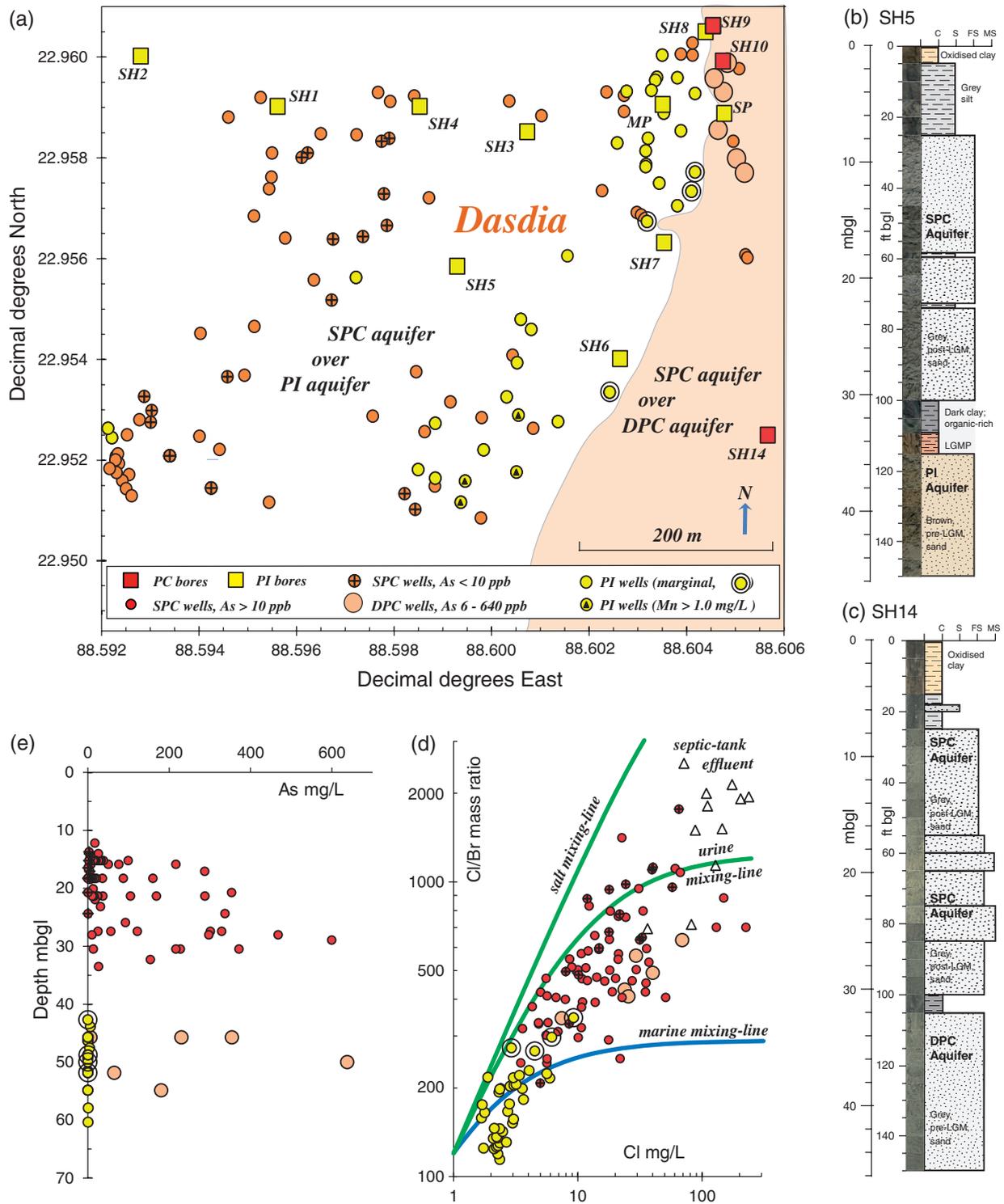
Figure 6. (a) Distribution across the most densely sampled part of Dasdia, of wells in the SPC, DPC, and PI aquifers. **(b)** Lithological log SH14, typical of the PC sequence in the eastern part of the map area, where SPC sands overlie DPC sands. **(c)** Lithological log SH5, typical of the sequence found in the remainder of the map area, where SPC sands overlie a PI aquifer capped by the LGMP. **(d)** Cl/Br v Cl in well water; mixing lines and end-members from McArthur et al. (2012b). **(e)** Concentrations of As in well waters plotted against well depth.

to tap the PI aquifer, none would be polluted by As. With Argos et al. (2010) finding that consuming groundwater with >10 µg/L As brings a 22% risk of dying from As-related disease, the cost/benefit ratio of drilling deeper seems worthwhile. The cost of so doing would probably

have been acceptable to owners had the outcome of doing so been known at the time of drilling.

High values of Cl/Br in groundwater are proof of contamination by waste water (Davis et al. 1998; Vengosh and Pankratov 1998). Values are high in 92%

of SPC groundwaters across Dasdia but are low in PI groundwaters, excepting a few at the PI margins (Figure 6d; Table S2). The contrast between PI and SPC groundwaters attests to the robust protection afforded by the LGMP to downward migration of Cl, a mobile, conservative, tracer, and so on, to all pollution in the SPC aquifer. Waste water has yet to affect groundwater in the PI aquifer under a village established for over 150 years.

Across Dasdia, 17 wells tapping the SPC aquifer yield groundwater containing <10 µg/L As, and it is important to understand why they are not As-polluted. The Cl/Br in most (Figure 6d) shows that they have been heavily influenced by waste water, which is known to reduce concentrations of As in groundwater of the Bengal Basin (McArthur et al. 2012b). The few remaining SPC wells with As concentrations <10 µg/L are too shallow (Figure 6e) for the groundwater to have evolved chemically to the point of FeOOH reduction, the process that releases As to groundwater (Gulens et al. 1979 et seq.). Installation of very shallow wells therefore affords a mitigation strategy. It is an uncertain strategy, however, because of the risk from surface contamination and pollution. In such wells, the risk of As pollution may be substituted by a risk of microbial pollution. For successful mitigation, very shallow wells (i.e., <20 mbgl) should be sited away from latrines, and that may not be achievable for pragmatic reasons.

Protection from Lateral Invasion

The groundwater in the PI aquifer at Dasdia, and in PI aquifers elsewhere, is currently As-safe. The length of time it will stay that way will be determined by the capacity of the PI aquifers, both their upper brown sand and their lower gray sand, to retard As in groundwater recharging from adjacent PC aquifers. Modeling such movement is beyond the scope of this paper, but pertinent observations may be made.

The first observation is that, to our knowledge, no reports exist of the sorption capacity of gray, pre-LGM sand. Its capacity to sorb As is likely to be lower than that of the brown PI sands. Deeper PI aquifers of gray sand may therefore be at risk of As pollution in the long term. The second observation is that As in groundwater recharging laterally from DPC aquifers and moving through brown sands does not appear to be a threat for wells more than a few tens of meters from PI margins. Retardation rates for As migration through brown PI sands of the Bengal Basin are in the region of 30 to 70 (Stollenwerk et al. 2007; Hoque et al. 2014) although values of 16 to 20 were estimated for a late Pleistocene setting in Vietnam (van Geen et al. 2014). Measurements of rates of horizontal groundwater flow in the Bengal Basin are rare, but values of around 30 m per year (McArthur et al. 2008) and 63 m per year (Sikdar et al. 2013), in response to irrigation pumping from beneath a PI aquifer, were estimated for Moyna, West Bengal. The As pollution front therefore moves, perhaps, at a rate of <1 m per year in the Bengal Basin. Such a rate is consistent with groundwater flow rates at Moyna and with the fact

that As concentrations in groundwater at Moyna remains in 2014 below 5 µg/L in piezometers and wells installed in 2004 in PI brown sands 30 m downflow of the PI margin (Piezometer DP of McArthur et al. 2004). Given that PI aquifers may be kilometers in continuous lateral extent, setting wells away from the margin of PI aquifers, and setting sentinel wells at PI margins, therefore appears to be a viable long-term option for mitigation.

The Mn Problem

Although low in As, groundwaters from PI aquifers of brown sand tend to be high in Mn (DPHE 1999, 2001; van Geen et al. 2007; Hug et al. 2011). Across our area, concentrations of Mn do not exceed 1.4 mg/L and only 6% of PI groundwaters contain more than 1.0 mg/L Mn. These Mn-rich wells are located on PI margins, where they probably mark redox fronts developed as PC water laterally invades PI aquifers, as has been shown to occur elsewhere in West Bengal (McArthur et al. 2012a). Concentrations of Mn in groundwater from the PI interior in our present study area are mostly <0.4 mg/L.

Prior to 2011, after which year it was discontinued, the WHO Guideline Value for Mn in drinking water was 0.4 mg/L (WHO 2008). When present in drinking water in concentrations up to several mg/L, manganese may impair the intellectual development in children (Wasserman et al. 2006). The substitution of As-polluted groundwaters in PC aquifers by Mn-rich groundwaters from PI aquifers of brown sand therefore carries with it an element of risk substitution, although we note that such concentrations may also be beneficial during pregnancy (Rahman et al. 2013). Excepting for school wells, exploitation of brown PI aquifers may offer an acceptable risk substitution of Mn for As, given the evidence that As is such a hazard to health in the Bengal Basin.

Are PI Aquifers Widespread?

It can be argued that palaeo-interfluves with capping LGMP, although ubiquitous at the LGM, have been largely eroded by river incision since 6000 ka, when sea level rose to around its present level. If so, their prospective value for mitigation is diminished. Widespread river avulsion since 6 ka in the Bengal Basin is evidenced by the widespread channel scars seen on satellite imagery. The Brahmaputra River has changed course within recent memory (Coleman 1969) and before (Pickering et al. 2013), and the Ganges has changed course over Holocene time, from straight south from the Rajmahal Gap to SW at the present day (Morgan and McIntire 1959). The migration of such large rivers might be expected to scour deeply enough to remove the LGMP and much underlying PI brown sand.

Despite the above, drilling at many spot locations across the Bengal Basin appears to confirm that PI and a capping LGMP are widespread (Umitsu 1993; Goodbred and Kuehl 2000a, 2000b; Pate et al. 2009) and that the PI sands comprise viable aquifers (van Geen et al. 2003a; McArthur et al. 2004; Zheng et al. 2005; von Brömssen et al. 2008). In our area, and in the area of

Biswas et al. (2014) to the north of it, buried palaeo-interfluves, with capping palaeosol, are preserved. Other multisite investigations (McArthur et al. 2011; Hoque et al. 2012) show that PI aquifers and the capping LGMP are widespread in southern West Bengal at a depth that is both locally predictable and shallow enough to be accessible to most of the rural poor. That predictability is little impaired by the finding of rare, exceptionally thick, red clay sequences at MKB1, SKP1, and RTN (TableS1), which cannot represent the LGMP alone. One similar occurrence was found by Biswas et al. 2014 to the north of our study area, but no explanation of its origin was given by those authors. These rare thick red clays may be clay plugs infilling abandoned channels and cut-off meanders (Donselaar and Overeem 2008). Attention is drawn to these thick, red clays because of the possibility of their being taken to be the LGMP.

Hoque et al. (2014) recorded extensive PI aquifers along a 115 km traverse across central Bangladesh. Drilling on a traverse across the course of the Old Brahmaputra River in north-central Bangladesh (Pickering et al. 2013) revealed significant sections of LGMP flanking the Old Brahmaputra channel. Brown sand occurs beneath the LGM surface at 46 m depth in Srirampur, eastern Bangladesh (Lowers et al. 2007). At depth in eastern Bangladesh, Ravenscroft (2003, Figure 2) figured extensive brown sands that occurred well away from the upstanding Madhupur Tract. Whether the LGMP was also present is not recorded, probably because it is difficult to identify when using the rotary-drilling method employed.

In short, the available evidence suggests that shallow PI aquifers hosting low-As groundwater are widespread across the Bengal Basin and that they are often protected from pollution in groundwater of overlying aquifers by a clay cap, usually the LGMP. Their use in As mitigation, long delayed, should now be enacted on a basin-wide scale.

Conclusions

Using 76 drill holes and by analysis of 535 ground-water samples, the existence of palaeo-interfluvial (PI) aquifers that host groundwater containing <10 μg/L As has been documented across substantial parts of central West Bengal. The palaeo-interfluvial (PI) aquifers form two, north-south trending, subsurface features that are separated laterally by a DPC aquifer, and are flanked on the east by another DPC aquifer, both of which host As-polluted groundwater. The depth to the top of the PI aquifers is commonly no more than 38 mbgl, a depth sufficiently shallow for the aquifers to be tapped by the rural poor. The PI aquifers provide a source of water that, with the possible exception of Mn in a small proportion of wells, is free of the hazards posed by the impact of both waste water and natural pollution.

Across most of the study area SPC aquifers at depths <38 mbgl overlie both PI and DPC aquifers and hosts As-polluted groundwater. Exploitation of the SPC aquifers in preference to slightly deeper PI aquifers has imposed a needless burden on the health of the rural poor. Substantial mitigation of As pollution present in groundwater from SPC aquifers across 95% of Dasdia, and across 30% of the wider study area, could be achieved by the simple expedient of drilling wells a little deeper, so that they tap the PI aquifer.

This work confirms that the distribution of As pollution of shallow groundwater across the Bengal Basin is controlled by the disposition of unpolluted, pre-LGM, palaeo-interfluvial aquifers capped by a palaeosol, and polluted, post-LGM, palaeo-channel aquifers of gray sand. In order to further validate these conclusions, the subsurface sedimentology of the Bengal Basin should continue to be explored by color mapping of well completions, drilling, and well-water analysis, in order to map further the extent of the palaeo-interfluves and palaeo-channels as an aid to the mitigation of As pollution.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Drilling locations and depths to the top of the late Pleistocene brown sands, where present.
Table S2. Composition of well waters.

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