Science of the Total Environment 493 (2014) 615–625

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Sediment color tool for targeting arsenic-safe aquifers for the installation of shallow drinking water tubewells

Mohammed Hossain [a,b,*], Prosun Bhattacharya [a,*], Shaun K. Frape [c], Gunnar Jacks [a], M. Mainul Islam [b], M. Moklesur Rahman [d], Mattias von Brömssen [a,e], M. Aziz Hasan [d], Kazi Matin Ahmed [d]

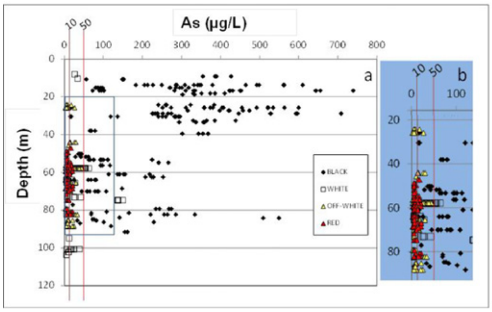
[a] KTH-International Groundwater Arsenic Research Group, Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Teknikringen 76, SE-100 44 Stockholm, Sweden
[b] NGO-Forum for Public Health, 4-6/Block-E, Lalmatia, Dhaka 1207, Bangladesh
[c] Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, ON N2L 3G1, Canada
[d] Department of Geology, University of Dhaka, Dhaka 1000, Bangladesh
[e] Soil and Water Environment, Ramböll Sweden AB, SE-104 62 Stockholm, Sweden

HIGHLIGHTS

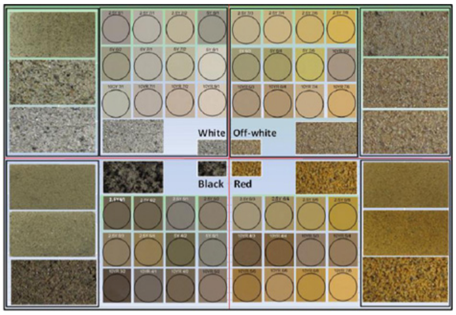
- More than 90% tubewells in Bangladesh are installed privately by the community.
- Local drillers are the main driving force in tubewell installations.
- Long term monitoring validated arsenic in water with respect to sediment color.
- A sediment color tool is developed based on local driller's color perception.
- This tool would play a significant role to scale-up safe water access.

GRAPHICAL ABSTRACT

Arsenic monitoring in groundwater from four sediment color groups



Sediment Color Tool



ARTICLE INFO

Article history:
Received 17 March 2014
Received in revised form 8 May 2014
Accepted 8 May 2014
Available online 28 June 2014

Editor D. Barcelo

Keywords:
Arsenic
Bangladesh
Tubewell
Local driller
Sediment color tool
Sustainable mitigation

ABSTRACT

In rural Bangladesh, drinking water supply mostly comes from shallow hand tubewells installed manually by the local drillers, the main driving force in tubewell installation. This study was aimed at developing a sediment color tool on the basis of local driller's perception of sediment color, arsenic (As) concentration of tubewell waters and respective color of aquifer sediments. Laboratory analysis of 521 groundwater samples collected from 144 wells during 2009 to 2011 indicate that As concentrations in groundwater were generally higher in the black colored sediments with an average of 239 µg/L. All 39 wells producing water from red sediments provide safe water following the Bangladesh drinking water standard for As (50 µg/L) where mean and median values were less than the WHO guideline value of 10 µg/L. Observations for off-white sediments were also quite similar. White sediments were rare and seemed to be less important for well installations at shallow depths. A total of 2240 sediment samples were collected at intervals of 1.5 m down to depths of 100 m at 15 locations spread over a 410 km^2 area in Matlab, Bangladesh and compared with the Munsell Color Chart with the purpose of direct comparison of sediment color in a consistent manner. All samples were assigned with Munsell Color and Munsell Code, which eventually led to identify 60 color shade varieties which were narrowed to four colors (black, white, off-white and red) as perceived and used by the local drillers. During the process of color grouping,

---

[*] Corresponding authors at: KTH-International Groundwater Arsenic Research Group, Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Teknikringen 76, SE-100 44 Stockholm, Sweden. M. Hossain: Tel.: +46 8 790 8063, +46 70 400 3498 (Mobile); P. Bhattacharya: Tel:+46 8 790 7399, +46 70 697 4241 (Mobile).
E-mail addresses: mohhos@kth.se, mohammed_hossain2001@yahoo.com (M. Hossain), prosun@kth.se (P. Bhattacharya).

http://dx.doi.org/10.1016/j.scitotenv.2014.05.064

participatory approach was considered taking the opinions of local drillers, technicians, and geologists into account. This simplified sediment color tool can be used conveniently during shallow tubewell installation and thus shows the potential for educating local drillers to target safe aquifers on the basis of the color characteristics of the sediments.

---

1. Introduction

Access to safe water supply is a basic human right and one of the most essential requisites of good health. Natural arsenic (As) in groundwater exposes millions of people to health risks of various magnitudes through drinking water and is a big challenge globally (Bundschuh et al., 2010). A recent publication (Argos et al., 2010) has raised serious concern that incidences of As in drinking water would cause a large number of deaths due to cancer alone if the problem is not properly managed.

For drinking water supply, the Bangladeshi population almost entirely depends upon groundwater sources. The remarkable achievement in reducing the scale of cholera and diarrheal diseases and infant mortality in the 1970s and 80s became possible from the increased use of groundwater for drinking (Steer and Evans, 2011). The occurrence of natural As in groundwater and its exposure drastically reduced the safe water access across the country with more severity in the southern half. In cities and urban areas, the supply is based on a piped water supply system. But in rural Bangladesh, water supply is mostly obtained by manually operated hand pumps in tubewells installed by the communities themselves.

Despite significant progress in our understanding of the source and distribution of arsenic (As), and its mobilization through sediment–water interactions (Bhattacharya et al., 1997, 2002; Nickson et al., 1998; BGS, DPHE, 1999, 2001; Harvey et al., 2002; van Geen et al., 2003; Ahmed et al., 2004; Islam et al., 2004; Mukherjee and Bhattacharya, 2001; McArthur et al., 2004; Charlet et al., 2007; Saunders et al., 2005; Polizzotto et al., 2008; Nath et al., 2009; Polya and Charlet, 2009; Bundschuh et al., 2010; Mukherjee et al., 2011; Biswas et al., 2012a, 2012b), there has been limited success in mitigation attempts in Bangladesh (Ahmed et al., 2006). A social survey conducted in 96 villages of Matlab for a parallel study by the same research group during 2009–2011 revealed that only 18% of the total tubewells provided safe water. Among these, the safe water access also varied widely between 0 and 90% with respect to the total tubewells installed in villages surveyed (SASMIT Annual Report, 2011; Hossain et al., 2012). In addition to poverty, unplanned development programs and lack of awareness, inadequate knowledge of local geology was also found as an important cause for installing tubewells in unsafe aquifers.

Different alternative safe drinking water options, such as, Arsenic Removal Filter (ARF), Rain Water Harvester (RWH), Pond Sand Filter (PSF), and Arsenic-safe tubewells have been provided in various affected areas in Bangladesh (Jakariya et al., 2005, 2007; Inauen et al., 2013). A recent evaluation of these options conducted in Matlab (Hossain et al., 2011) reveals that the tubewells are the most widely accepted option with almost no-cost of operation and availability of good quality water throughout the year.

At present, the main problem is the huge gap between the extent of exposure and the pace of mitigation. Therefore the main challenge is to develop a simple cost-effective tubewell option which would be easily acceptable by the people and possible to install and maintain by themselves. Hand percussion drilling is the most common method of tubewell installation used by the local drillers. This is a local technology, cost-effective and needs readily available inexpensive equipment. Although government programs and non-government projects extend their cooperation through installation of tubewells, nevertheless most of the tubewells (about 90% in the whole country) are installed by the community with the help of the local drillers.

In order to change the scenario of safe water access in the arsenic affected areas, importance largely lies with the development of a method/tool by which the local drillers can identify and target safe aquifers without the aid of technical expertise. This kind of knowledge and education of the local drillers can be extremely useful in scaling-up safe water access.

Based on the color perception of the local drillers, the four color (black, white, red, off-white) hypothesis was proposed by von Brömssen et al. (2007) based on the study carried out in two villages of Matlab. The relationship of aquifers' sediment color and corresponding As concentration in waters derived from those sediments was evaluated based on monitoring of 40 wells sampled in May 2004. Color of screen layer sediments was depicted mainly by the respective drillers who had installed the wells before the study. Local drillers have been installing tubewells targeting red/off-white aquifers for low-iron water for the last few years and eventually now they have acquired the knowledge that the color could be related to As concentration in tubewell water. Relevance of sediment color with respect to As in water has also been reported from Araihazar (e.g. van Geen et al., 2004), Savar (e.g. Stollenwerk et al., 2007) and this study area Matlab (e.g. Hossain et al., 2010a) and Munshiganj (e.g. Hug et al., 2011) in Bangladesh and West Bengal, India (McArthur et al., 2004; Pal and Mukherjee, 2008, 2009; Datta et al., 2011; Biswas et al., 2012a, 2012b, 2014), which reflects similar observations from a wider geographic range. According to the existing four color hypothesis as shown in Fig. 1, highest risk lies with the black color sediments and gradually reduces towards red. Although we are dealing with four colors, black and red colors carry more importance considering their wider occurrence in the field of shallow tubewell installation.

The main objective of this study is to validate the four color hypothesis through an extensive hydrogeological investigation and thereafter to develop a sediment color tool (Hossain et al., 2010b, 2013) for a wider spatial coverage at different depths so that the driller's perception have a scientific basis for targeting arsenic-safe aquifers. If the drillers can identify the aquifers in the field, it would bring a significant change to minimize the gap between arsenic exposure and safe water access in rural Bangladesh.

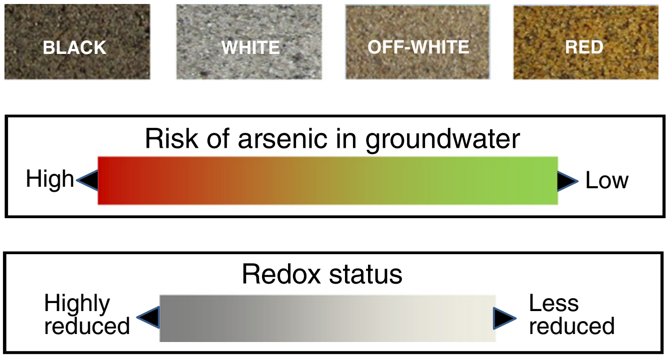


Fig. 1. Four color sands with corresponding risks of As concentration in water under varying redox status.

2. Material and methods

2.1. Study area

The Matlab region (Fig. 2a–b) located in the southeastern part of Bangladesh was chosen as the study area because of three important reasons — (a) a severely affected area from arsenic contamination, (b) safe water access is very limited, and (c) intensively investigated from scientific, social and health aspects of arsenic.

The study area constitutes a portion of the Bengal Delta which lies near the confluence of the three major rivers, the Ganges, the Brahmaputra and the Meghna. Geomorphologically, the study area characterized by vast flat plain, meander channels, natural levees, ox-bow lakes, and back swamps is a low-lying area (3–10 m asl measured by this study) where agriculture is the main land use pattern. According to Morgan and McIntire (1959) and Bakr (1977), this area is constituted by Chandina Deltaic Plain (also known as Tippera Surface) stretched in the east and mostly by Meghna Flood Plain in the west. Both units comprise mainly clay, silt and sand. Present day river Meghna and its tributaries formed Meghna Flood Plain deposits, while the Chandina Formation is rather compacted, weathered and more oxidized.

2.2. Test boring and installation of depth and color specific monitoring wells

For a comprehensive hydrogeological investigation through sediment characterization and monitoring water quality, this study conducted test borings in 15 locations targeting shallow, intermediate and deep aquifers (Fig. 2c). For shallow borings, an exclusively hand-percussion (sludger) method was used. Deep borings were done up to a depth of 250 m, and rotary reverse-circulation drilling (locally called the Donkey method) was used. For the intermediate deep ones, both hand-percussion and the Donkey method were used depending on driller's knowledge about specific site characteristics. Visualizing the subsurface geology using borelogs, 78 piezometers were installed for groundwater monitoring in these 15 sites. In deciding the screen positions of the monitoring wells, some specific criteria, such as, different aquifers with varied sand color, depth of high (peak) arsenic in tubewell water (revealed from the analysis of secondary data) and water table fluctuation data collected from Bangladesh Water Development Board (BWDB) were considered.

For this study, we have considered the observations made up to a depth of 100 m for both sediment samples and water quality with the purpose of developing a color based tool which could be used by the drillers to target safe aquifers within shallow depth using hand-percussion drilling.

2.3. Sediment sampling and characterization

Sediment samples were collected from each 1.5 m (5 ft) section during boring. From 15 locations, sediment sample collection up to a depth of 100 m (330 ft) provided us 2240 samples which have been characterized based on their grain size and color. For grain size, clay, silt, fine sand, medium sand and coarse sand were determined with the aid of visual inspection. For assigning color, visually observed color was recorded first and then sediments were compared with the Munsell Color Chart with the purpose of standardization of color characteristics through a scientific method that allows a methodical re-examination and replication in the study area and elsewhere in the same manner.

The Munsell Color System (Munsell Color x-rite, 2009) comprises thirteen charts describing colors by an arrangement of three dimensions — Hue, Value and Chroma. The Hue notation reflects the color with respect to red, yellow, green, blue and purple. Value indicates the degree of lightness — in a vertical scale color gradually becomes light from bottom to top in visually equal steps with the increasing number. In the similar fashion, Chroma notation indicates its strength with respect to the neutral of the same lightness — in a horizontal scale which increases from left to right. The use of Munsell color codes in describing the sediments made them distinctive from each other and thus reduces the risk for misinterpretation of the sediment colors.

The color characterization of sediments and the narrow down process to develop the color tool have been very simple and carried out as below:

Step-1 Immediately after collection of sediment sample, each of them was described based on the visual inspection in the moist condition and this color has been recorded as 'field observed color'.

Step-2 Each sample was then compared with the Munsell Color Chart and using this chart Munsell Color and Munsell Code were recorded respectively. These two steps (1 and 2) eventually led to finding all possible color varieties.

Step-3 In the narrow down process, each sample was finally assigned to one of the four colors — black, white, off-white and red (Fig. 3).

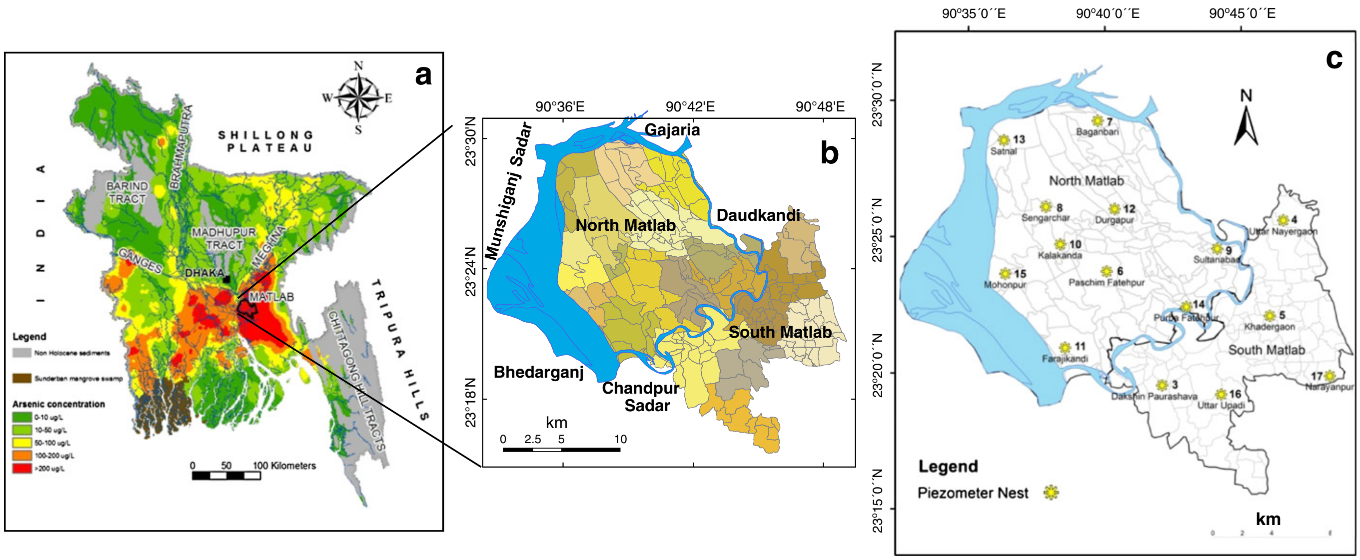


Fig. 2. Map of Bangladesh (a) with the location of the study area (b) and sites of test borings and installed piezometer nests (c).

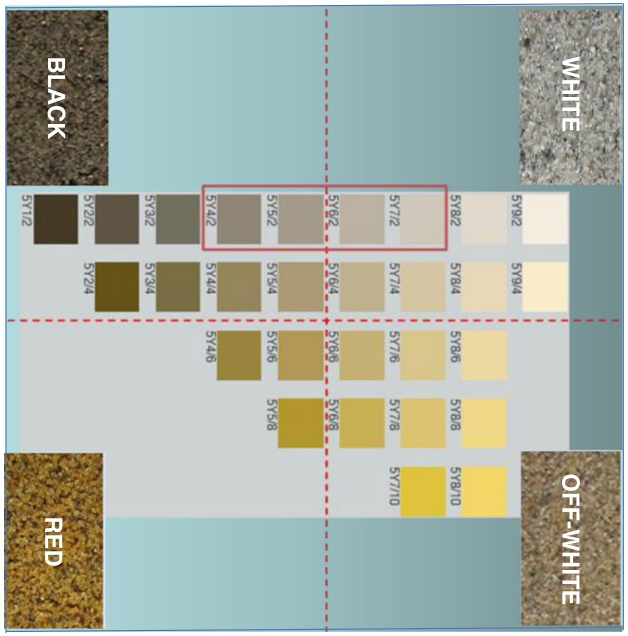


Fig. 3. Four colors as described by the local drillers on a Munsell Color Chart 5Y Hue (Modified from Unpublished SASMIT Report, 2011).

These four colors are the driller's perception of sediment color which they have gained through their work experience. During the assignment of four colors, participatory approach was considered with utmost importance taking the opinions of local drillers, field geologists and technical experts into account.

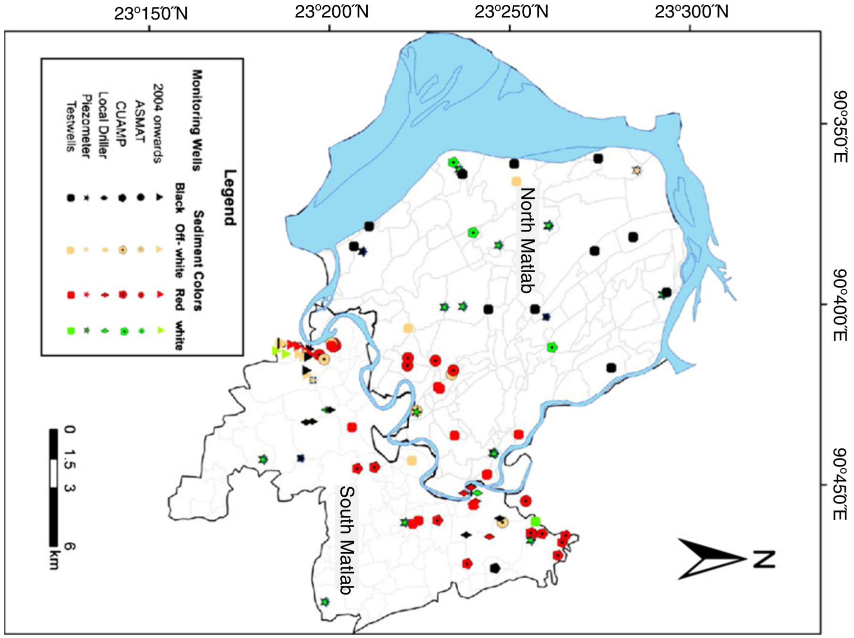


Fig. 4. Location of the monitoring wells with respect to the color of aquifer sediments.

Table 1
Overview of the drinking water wells and piezometers used for water chemistry monitoring.

Source/agency installed	No. of wells	No. of water samples considered	Depth range (m)	Period of monitoring	Remarks on aquifer sediment color	Black	White	Off-white	Red	Sub-total
Private drinking water wells which have been monitored by other KTH studies since 2004	18	139	24–79	2004–2011 Post-Monsoon	Sediment color was collected by a previous study (von Brömssen et al., 2007) and has been rechecked with respective drillers by this study	5	2	7	4	18
Drinking water wells installed by AsMat — a Sida financed project (2000–2006)	14	54	52–88	2009 Premonsoon–2010 Postmonsoon	Borelogs were recorded by AsMat project. Respective well owners and drillers were interviewed again by this study	–	–	6	8	14
CUAMP (Columbia University, NY — NGOF) Project installed wells during 2009–2012	12	18	56–82	2009 Postmonsoon–2010 Postmonsoon	Sediment samples were collected and characterized by this study during the installation of the wells by CUAMP	1	–	3	8	12
Private wells installed by local drillers	16	56	26–91	2009 Premonsoon–2010 Postmonsoon	Sediment color info was collected from the local drillers by this study during well installation	8	2	–	6	16
SASMIT piezometers installed by this study	57	223	9–104	2009 Premonsoon–2011 Postmonsoon	Boring, sediment characterization and well installation was done by this study	41	9	5	2	57
SASMIT test wells installed by this study	27	31	46–88	2010 Premonsoon–2010 Postmonsoon	Boring, sediment characterization and well installation was done by this study	11	1	4	11	27
Total	144	521				66	14	25	39	144

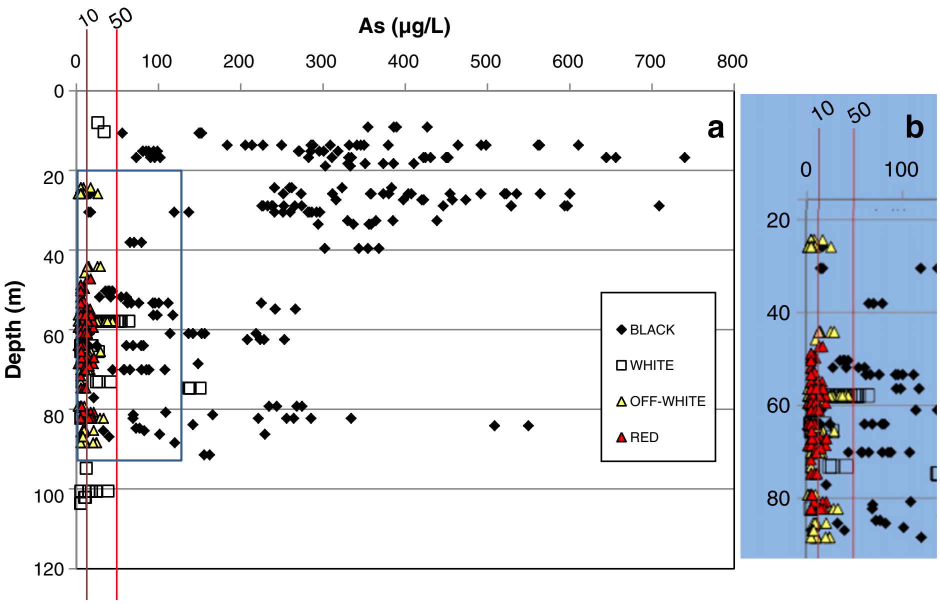


Fig. 5. The concentration of As in groundwaters derived from the sediments of the four color groups: a) with respect to depth; b) enlarged view of the levels of As in the red and off-white groups.

2.4. Water sampling and analysis

Groundwater samples were collected during the period between 2009 Pre-Monsoon and 2011 Post-Monsoon from 144 wells (Fig. 4) for which the study team has been confident about the color of the aquifer sediments, where the well screens were installed. Among these wells, 87 are drinking water tubewells and 57 monitoring piezometers. In our monitoring network for this study we have included 18 wells that have been monitored by other studies at KTH since 2004 (Jonsson and Lundell, 2004; von Brömssen et al., 2007; Robinson et al., 2011). An overview of wells monitored during this study is summarized in Table 1, which also provides the approach for confirmation of the color of the aquifer sediments.

Sampling was carried out following the procedure as described by Bhattacharya et al. (2002). Wells were purged before measurements of on-site parameters and collection of water samples in order to get data representative of the actual groundwater flow. Redox potential (Eh), pH, electrical conductivity (EC) and temperature were measured using the portable field meters which were calibrated at least once daily. Radiometer Copenhagen pH C2401-7 electrode was used for measuring the pH, while Eh was measured by a Radiometer Copenhagen MC408pt combination electrode. The measured redox potentials were later corrected with respect to the standard hydrogen electrode (+244 mV). Measurements of electrical conductivity and temperature were taken by Aqualytic portable meter (CD 22). All samples were filtered during collection using 0.45 μm Sartorius single use membrane filters. Samples collected in polyethylene bottle for cation and trace element analysis were acidified with Merck suprapure HNO_3, and samples for anion analysis were collected without acidification. Major anions (F^-, Cl^-, NO_3^- and SO_4^{2-}), PO_4^{3-}-P and NH_4^+-N were measured with Aquatec 5400 analyzer equipped with a Dionex DX-120 ion chromatograph in an IonPac As14 column at the water chemistry laboratory of the Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Stockholm, Sweden. In the same laboratory, dissolved organic carbon (DOC) in water was measured on a Shimadzu 5000 TOC analyzer. Arsenic along with other trace elements and major cations (Na^+, Ca^{2+}, Mg^{2+} and K^+) were analyzed by inductively coupled plasma optical emission spectrometry (Varian Vista-PRO Simultaneous ICP-OES equipped with SPS-5 autosampler) at the laboratory of the Department of Geological Sciences, Stockholm University, Sweden. During laboratory analysis, synthetic chemical standards and the duplicates were analyzed after every 10 samples. In all cases, concentrations of trace elements in the certified and synthetic standard (NIST SRM 1643) were found within ± 10% of their true values. For checking accuracy and precision of the results, replicate analyses were carried out which indicated variations within the range of ± 10%.

3. Results

3.1. As concentration in groundwater from aquifers assigned with four colors

The distribution patterns of black sediments show a wide range of variability in terms of depth and As concentration (Fig. 5), although a significant proportion (50%) of wells (n = 66) installed in black sediments are located within a very shallow depth range of 10–40 m. Arsenic in black sediment aquifers show the wide range of

Table 2
Summary of As concentration in waters derived from aquifers assigned with four colors.

Aquifer's sediment color	No. of wells	Depth range (m)	No. of samples analyzed	No. of wells comply with BDWS	% of wells comply with BDWS	No. of wells comply with WHO guideline	% of wells comply with WHO guideline	Max (μg/L)	Min (μg/L)	Mean (μg/L)	Median (μg/L)
Black	66	9–91	230	11	17%	6	9%	739.8	5.6	239.2	240.1
White	14	58–104	49	10	71%	3	21%	150.6	5.6	36.1	27.7
Off-white	25	24–88	119	22	88%	15	60%	43.9	2.6	12.1	8.4
Red	39	47–82	123	39	100%	24	62%	21.8	2.6	9.4	8.6
Total	144		521								

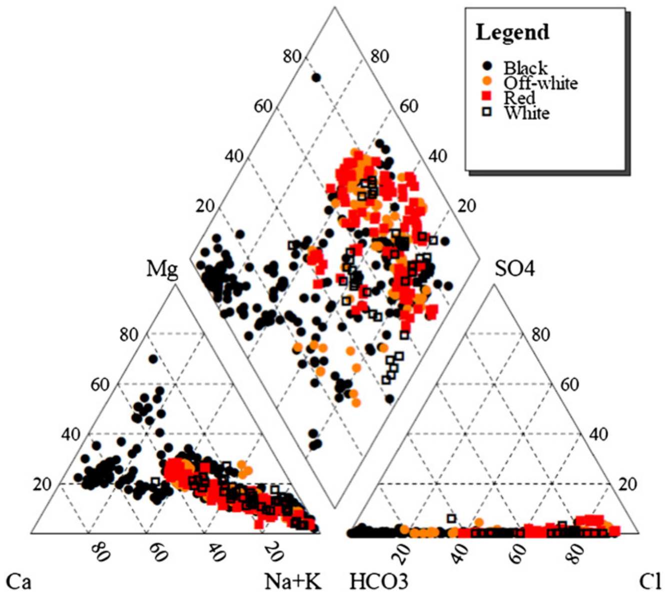


Fig. 6. Major ion composition of groundwater derived from the sediments of the four color groups plotted on a piper diagram.

concentrations, but skewed towards higher values. Average value is as high as 239 μg/L and a very limited number of wells comply with the Bangladesh drinking water standard and WHO guideline values (Table 2). Considering the probability of As-enrichment in water abstracted from black-colored sediments, they are assigned as 'high-risk' in the hypothesis which is clearly revealed from the results of the current study.

Arsenic in water samples collected from 39 wells abstracting water from red color sediments provides safe water following the Bangladesh drinking water standard of 50 μg/L. Average and median values are less than the WHO guideline value of 10 μg/L (Table 2). Depth of these red sediment wells is between 47 and 82 m. In terms of depth and As concentration in water, 25 wells installed in off-white aquifers are similar to red sands to a large extent. White color sediments were recorded from only 14 wells and all of them are installed below the depth of 55 m. The white sediments seemed of less importance as aquifers for tubewell installation at shallow depths.

3.2. Hydrochemical variation in groundwater from aquifers assigned with four colors

Major ion chemistry and water types are presented in Fig. 6. Groundwaters abstracted from black sediments are characterized mainly by Ca–Mg–HCO_3 to Na–Cl–HCO_3 type, while the water samples collected from white and red sediments are predominantly Na–Cl–HCO_3 type. Predominance of Ca and Mg was also observed in waters derived from off-white aquifers.

Redox sensitive parameters along with As concentrations observed from groundwaters sampled from all four color sediments are summarized in Table 3. Groundwaters derived from black sediments are characterized by elevated concentration of HCO_3^-, DOC, Fe^{2+}, NH_4^+ and PO_4^{3-} and very low Mn and SO_4^{2-} (Fig. 7). Relatively high Mn and SO_4^{2-} and low concentration of HCO_3^-, DOC, Fe^{2+}, NH_4^+ and PO_4^{3-} were observed in waters abstracted from red and off-white sediments. The concentration of SO_4^{2-} is in general low, except some wells located in Uttar Nayergaon area in the northeastern part of the study area around piezometer nest 4. These high sulfates are also associated with high Na and Cl. A kind of mixed characteristic was observed in groundwaters derived from white sediments. For Mn, Fe^{2+} and SO_4^{2-} these are similar to the black group; and HCO_3^- and DOC concentrations are in the same trend as in the red and off-white groups; while NH_4^+ and PO_4^{3-} are in between black and red sediments. Manganese was found high (>WHO previous guideline value of 0.4 mg/L) in waters abstracted from the red and off-white sediments and therefore the presence of elevated Mn could be a limiting factor for targeting red and/or off-white sands for tubewell installation. Groundwaters sampled from wells screened in black and white sediments contain relatively low Mn.

3.3. Sediment characterization, standardization and development of color tool

Sixty color varieties (Fig. 8) were identified taking all the sediment samples into account from different depths up to 100 m and 15 locations through detailed scrutiny of the sediment color and classification as described earlier. Bringing down all sixty color varieties into four major colors, it was possible to group different color shades which led to a simplified color tool (Fig. 9) for use in a convenient way for tubewell installation. Munsell color hue 2.5Y and 10YR were found to be most common in matching the sediment samples and in the process of grouping them into four color groups (black, white, off-white and red). Some of the color shades matched well with hue 5Y also. Munsell code 2.5Y 4/1 ↔ 5/4 and 10YR 3/2 ↔ 5/2 corresponding to Munsell color dark gray and dark grayish brown to light olive brown, olive and olive gray matched well under black color sediments. Munsell color shades located in the top-left part of the charts for hue 2.5Y, 5Y and 10YR, such as, light gray, light olive gray and white were best-fitted under white color group. Munsell colors ranging from pale yellow and yellow to pale olive and pale brown with respective codes 2.5Y 7/3 ↔ 7/8; 5Y 6/3 ↔ 7/6 and 10YR 6/2 ↔ 7/6 were found best suitable to be included in the off-white color group. Similarly, light yellowish brown and olive yellow to brown, yellowish brown and yellow color shades with

Table 3
Statistical summary of As. pH. Eh and redox sensitive parameters in waters from aquifers assigned with four sediment color groups.

Parameters	Black sediments No of wells: 66 No of samples: 230					White sediments No of wells: 14 No of samples: 49					Off-white sediments No of wells: 25 No of samples: 119					Red sediments No of wells: 39 No of samples: 123				
	Max	Min	Mean	Median	StdD	Max	Min	Mean	Median	StdD	Max	Min	Mean	Median	StdD	Max	Min	Mean	Median	StdD
As (μg/L)	740	5.6	239	240	175	151	5.6	36.1	27.7	35.3	43.9	2.6	12.1	8.4	9.6	21.8	2.6	9.4	8.6	4.9
Mn (mg/L)	4.0	0.01	0.7	0.3	0.8	2.1	0.04	0.5	0.3	0.5	4.3	0.02	2.0	1.9	1.2	4.8	0.2	2.0	1.8	1.0
Fe (mg/L)	40.3	0.01	6.5	5.2	5.3	30.9	0.81	7.1	6.8	5.4	10.8	0.07	2.0	0.7	2.5	18.9	0.01	1.7	0.47	3.4
SO_4 (mg/L)	39.3	0.01	1.9	0.7	3.5	20.7	0.01	1.4	0.5	3.1	54.4	0.01	3.9	1.6	8.1	72.9	0.01	5.7	1.1	14.3
HCO_3 (mg/L)	1052	122	454	427	204	465	84	276	274	89	641	87	227	183	122	648	61	222	206	97
DOC (mg/L)	29.6	1.4	9.6	8.0	6.0	11.5	1.3	4.8	3.9	2.9	9.8	0.3	3.5	2.9	2.5	10.3	0.6	4.5	4.5	2.9
NH_4-N (mg/L)	57.8	0.01	6.3	2.7	10.4	10.2	0.01	1.7	0.3	2.9	12.8	0.01	0.5	0.03	1.7	2.6	0.01	0.2	0.06	0.4
PO_4-P (mg/L)	11.5	0.01	1.7	1.2	1.9	4.7	0.01	1.1	0.7	1.4	3.7	0.01	0.3	0.09	0.5	0.8	0.01	0.1	0.04	0.1
pH	7.8	6.3	6.9	6.9	0.2	7.5	6.0	6.9	6.9	0.3	7.5	6.0	6.7	6.7	0.3	7.4	6.1	6.7	6.7	0.2
Eh (mV)	349	109	239	242	47	342	113	247	260	53	348	162	278	280	36	387	191	286	27	28

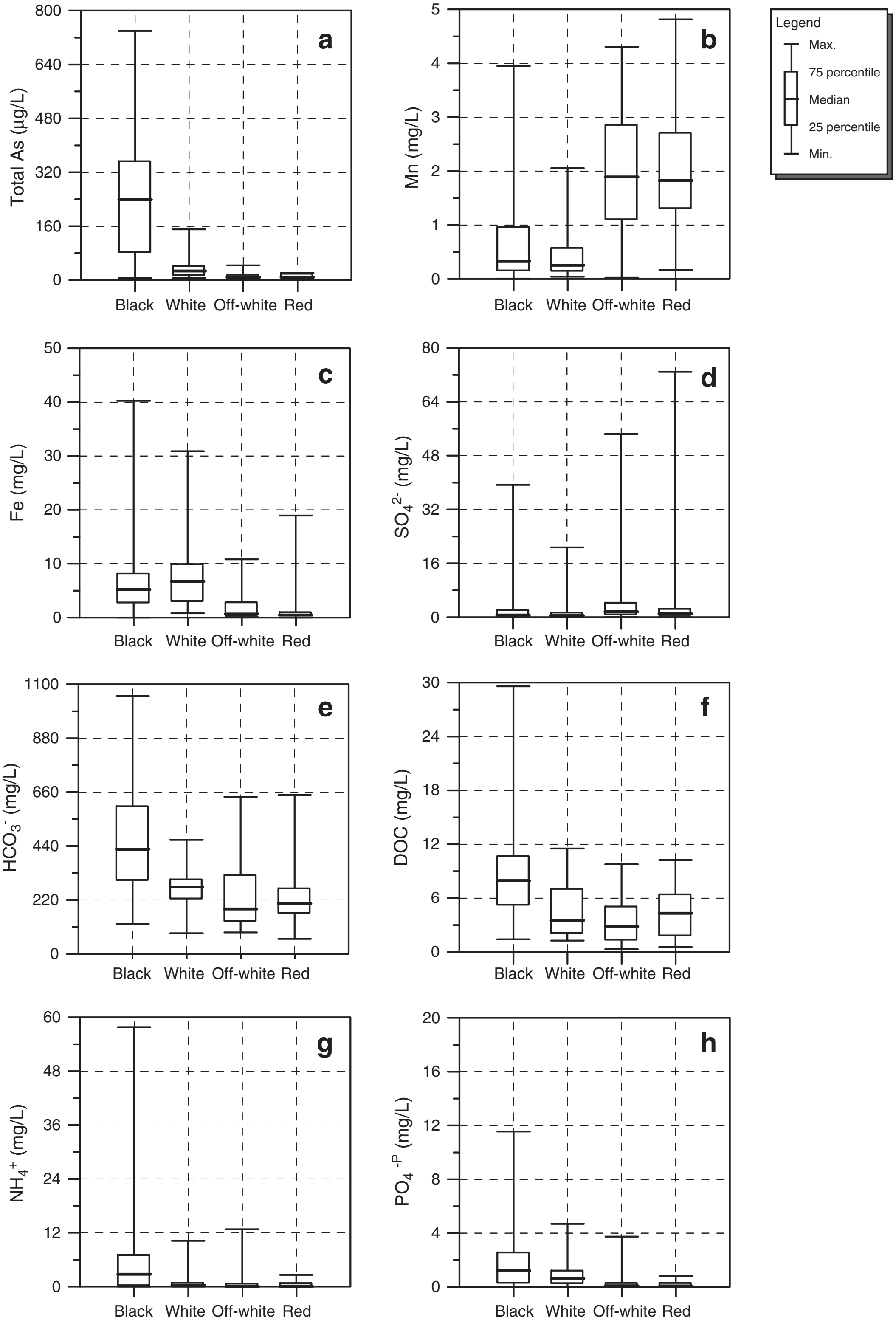


Fig. 7. Box plots showing the variations of (a) total As, (b) Mn, (c) Fe, (d) SO_4^{2-}, (e) HCO_3^-, (f) DOC, (g) NH_4^+ and (h) PO_4-P in groundwater samples derived from the aquifers assigned with respect to four colors.

corresponding codes of 2.5Y 6/3 ↔ 6/8 and 10YR 4/3 ↔ 7/8 located in the right-top corner of the respective Munsell charts were categorized under the red color group. For a few color shades, it was difficult to decide the appropriate color group due to their overlapping character and/or transition between two colors. Such examples are 2.5Y 6/1 (decided white but easily confused with 2.5Y 5/1 which is black); 2.5Y 7/3 assigned as off-white could be grouped as white also; and 10YR 5/3 seems good for black even although it was found better suitable under the red color group.

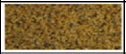
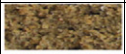
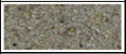
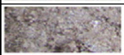
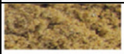
SL. (60 varieties)	Field Observed Colour	Munsell Color	Munsell Code	Visual Munsell Color	Photographic View of Sediment Sample	FOUR (4) COLOR	SL. (60 varieties)	Field Observed Colour	Munsell Color	Munsell Code	Visual Munsell Color	Photographic View of Sediment Sample	FOUR (4) COLOR
1	Light brownish GREY	BROWN	10YR 4/3	▨		RED	31	Brownish GREY	Light Olive BROWN	2.5Y 5/4	▨		BLACK
2	Dark GREY	BROWN	10YR 5/3	▨		RED	32	Greyish WHITE	Light Olive GREY	5Y 6/2	▨		WHITE
3	BROWN	Brownish YELLOW	10YR 6/6	▨		RED	33	Light GREY	Light Yellowish BROWN	10YR 6/4	▨		OFF-WHITE
4	BROWN	Brownish YELLOW	10YR 6/8	▨		RED	34	Whitish GREY	Light Yellowish BROWN	2.5Y 6/3	▨		RED
5	Light BROWN	Dark Greyish BROWN	10YR 4/2	▨		BLACK	35	Whitish GREY	Light Yellowish BROWN	2.5Y 6/4	▨		RED
6	Dark GREY	Dark Greyish BROWN	2.5Y 4/2	▨		BLACK	36	Light GREY	Light Olive BROWN	2.5Y 5/3	▨		BLACK
7	Dark GREY	Dark GREY	10YR 4/1	▨		BLACK	37	GREY	OLIVE	10YR 4/2	▨		BLACK
8	GREY	Dark Greyish BROWN	10YR 4/2	▨		BLACK	38	Dark GREY	Olive GREY	5Y 4/2	▨		BLACK
9	Greyish BROWN	Dark Greyish BROWN	2.5Y 4/2	▨		BLACK	39	Whitish GREY	Olive GREY	5Y 5/1	▨		BLACK
10	Whitish BROWN	Dark Yellowish BROWN	10YR 4/4	▨		RED	40	Light Brownish GREY	Olive YELLOW	2.5Y 6/6	▨		RED
11	Greenish GREY	Greyish BROWN	2.5Y 5/2	▨		BLACK	41	Light Brownish GREY	Olive YELLOW	2.5Y 6/8	▨		RED
12	Whitish GREY	Light greenish GREY	10GY 7/1	▨		WHITE	42	Light BROWN	Pale BROWN	10YR 6/3	▨		OFF-WHITE
13	GREY	Greenish GREY	2.5Y 5/1	▨		BLACK	43	Light GREY	Pale OLIVE	5Y 6/3	▨		OFF-WHITE
14	Dark GREY	Dark GREY	2.5Y 4/1	▨		BLACK	44	Light brownish GREY	Pale OLIVE	5Y 6/4	▨		OFF-WHITE
15	Whitish GREY	Yellowish BROWN	10 YR 5/4	▨		RED	45	Whitish GREY	Pale YELLOW	2.5Y 7/3	▨		OFF-WHITE
16	Light Greenish BROWN	Light Olive BROWN	2.5Y 5/3	▨		BLACK	46	Whitish GREY	Pale YELLOW	2.5Y 7/4	▨		OFF-WHITE
17	Whitish GREY	GREY	2.5Y 6/1	▨		WHITE	47	Greyish WHITE	Pale YELLOW	2.5Y 7/1	▨		WHITE
18	Light GREY	Greyish BROWN	2.5Y 5/2	▨		BLACK	48	Brownish GREY	Pale YELLOW	5Y 6/4	▨		OFF-WHITE
19	Whitish GREY	GREY	5Y 6/1	▨		WHITE	49	Brownish GREY	Very Dark Greyish BROWN	10YR 3/2	▨		BLACK
20	Light Brownish GREY	Greyish BROWN	10YR 5/2	▨		BLACK	50	GREY	Very Pale BROWN	10YR 7/4	▨		OFF-WHITE
21	GREY	Dark Greyish BROWN	2.5Y 4/2	▨		BLACK	51	Greyish WHITE	WHITE	5Y 8/1	▨		WHITE
22	Brownish GREY	Light Brownish GREY	10YR 6/2	▨		OFF-WHITE	52	Greyish WHITE	WHITE	10YR 8/1	▨		WHITE
23	GREY	Brownish YELLOW	10YR 6/6	▨		RED	53	Whitish GREY	YELLOW	10YR 7/6	▨		OFF-WHITE
24	Greyish WHITE	Light GREY	10YR 7/1	▨		WHITE	54	BROWN	YELLOW	10YR 7/8	▨		RED
25	Greyish WHITE	Light GREY	10YR 7/2	▨		WHITE	55	Brownish GREY	YELLOW	10YR 6/2	▨		OFF-WHITE
26	Whitish GREY	Light GREY	2.5Y 7/1	▨		WHITE	56	Whitish GREY	YELLOW	2.5Y 7/6	▨		OFF-WHITE
27	Whitish GREY	Light GREY	2.5Y 7/2	▨		WHITE	57	Light Yellowish BROWN	YELLOW	2.5Y 7/8	▨		OFF-WHITE
28	Whitish GREY	Light GREY	5Y 7/1	▨		WHITE	58	GREY	YELLOW	5Y 7/6	▨		OFF-WHITE
29	Light greyish WHITE	Light GREY	5Y 7/2	▨		WHITE	59	BROWN	Yellowish BROWN	10YR 5/4	▨		RED
30	Brownish GREY	Light Olive BROWN	2.5Y 5/3	▨		BLACK	60	Dark GREY	Yellowish BROWN	10YR 5/6	▨		RED

Fig. 8. Sixty varieties of sediment colors observed with respective four colors assigned.

Using this simplified color scheme that takes the range of observed sediment colors into consideration, any user can make a decision on the appropriateness of water supply for human consumption. In this simplification, we are not trying to set any concentration of arsenic with respect to the different color shades observed and categorized under each of the four color groups. Therefore, in this grouping process,

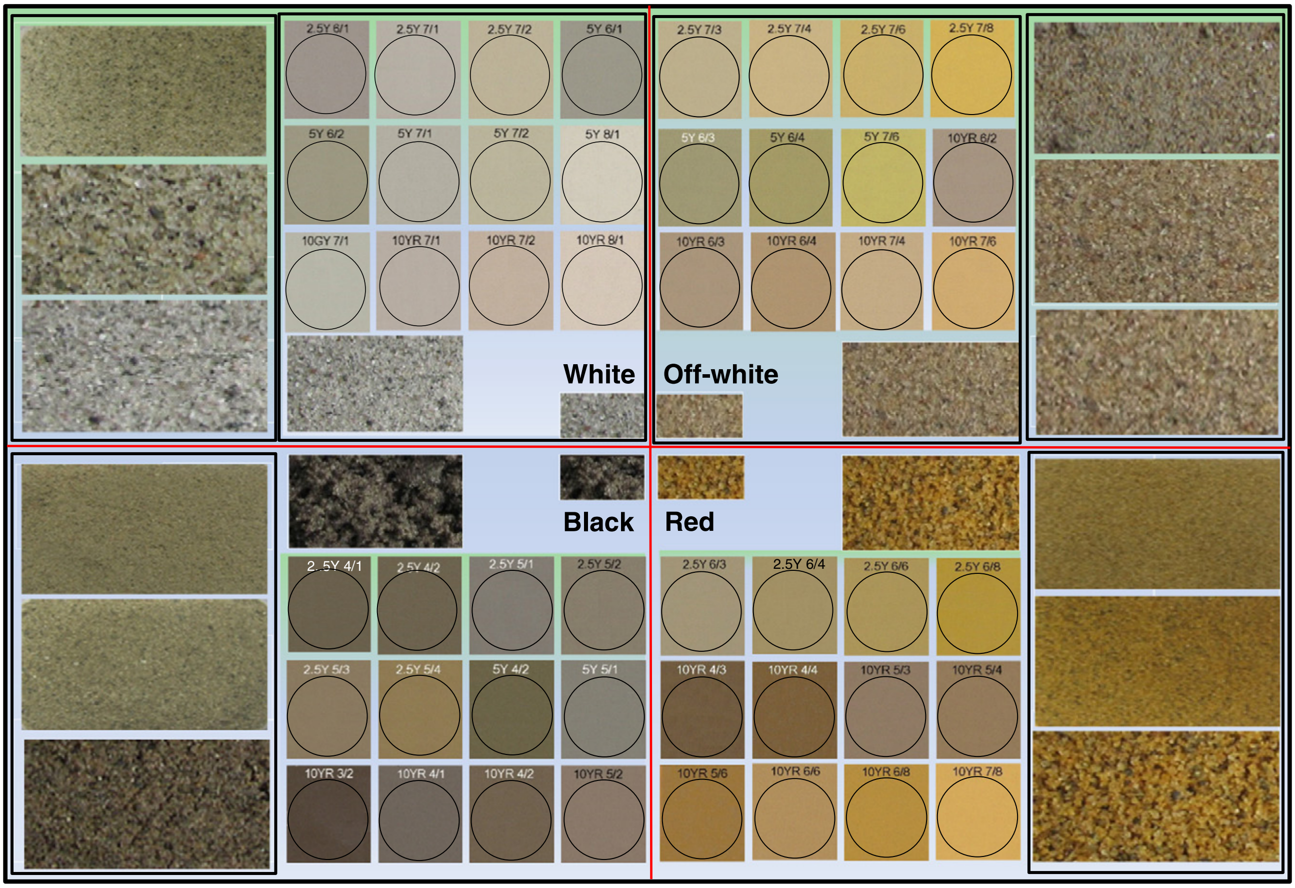


Fig. 9. A prototype of the simplified color tool for the use of local drillers for targeting safe aquifers at shallow depths (<100 m).

color as a whole is related to arsenic concentration, such as, black unsuitable and red suitable.

4. Discussion

According to the hypothesis that we are testing, black color sands have been designated as unsafe and in the high-risk group. Black sediments with high-As (≥50 μg/L) give a true-negative (Fig. 10) result, when this color tool is evaluated in terms of identifying potential problem aquifers. On the contrary, red sediments producing As-safe water give a true-positive result. Among 66 wells, all of which are installed in black colored sediments, 11 wells produce As-safe water with respect to Bangladesh drinking water standard (BDWS). Here we see that 17% ($n = 11$) of black sediments provide false-negative error, which means that these 17% wells are not unsafe as were expected because of black sediments. Low As in black sediments could be the result of highly reducing condition in the aquifers, when the stage of SO_4^{2-} reduction is reached. Under such condition, immobilization of As through co-precipitation with authigenic pyrite (Lowers et al., 2007; Nath et al., 2008) could cause low concentration of As in the water. Similarly, all wells in red colored sediments ($n = 39$) produce safe water with respect to BDWS; implying that 100% are true-positive and 0% false-positive. Here true positive means red sediments are considered positive as they produce As-safe water. When compared with the WHO guideline value, true-negative for black sediments accounts 91% and true-positive for red sediments comes 62%. These observations of high values of true-negative for black sediments and true-positive for red sands along with a mean and median value for As below WHO guideline strengthen the color hypothesis to a great extent.

External validation, observer's influence, and other limiting factors can be discussed with respect to the methods used and the results. As external validation of the tool, the studies conducted in severely As-contaminated areas in West Bengal, India (viz. Pal and Mukherjee, 2008, 2009; Datta et al., 2011; Biswas et al., 2012a, 2012b, 2014) provide similar results, where black sands produce mostly As contaminated water and red sands provide As-safe water.

During the coding of all sixty varieties, as a method, the use of Munsell color chart allowed us to reduce the possibility of making error to a great extent considering observer's influence as a factor of concern. But when each of the sixty varieties has been simplified into four color groups, the methodology was based on a participatory approach where the opinions of field geologists, technical experts and local drillers were taken into account. In this narrow down process, it is worth to mention that color perception is not the same to all people and there is no sharp contrast (defined boundary) between the colors. In this study, local driller's opinion was considered to be most important, as this four major color hypothesis was mainly developed based on their color perception gained through their work experience. In developing the simplified four color tool, very satisfactory agreement (more than 80%) was observed between the research team and local drillers and also among the drillers themselves. Time of the day and sun light could also play an important role in deciding the sediment color and thereby to make decision about the aquifer targeted for tubewell installation. This is more crucial for the identification of off-white color. Based on this study findings, an attempt was made to

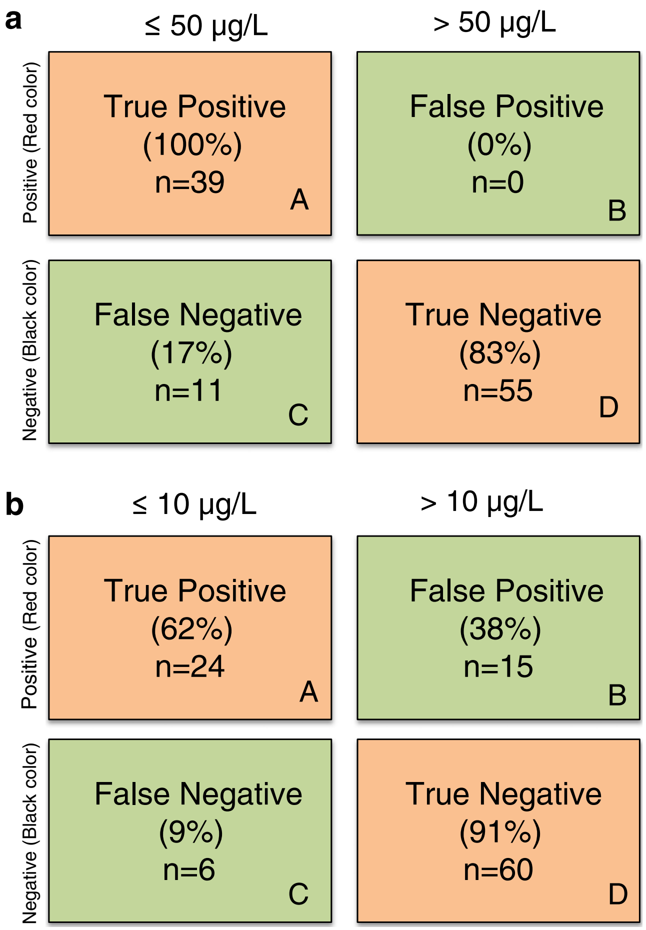


Fig. 10. Generic approach for the validation of sediment color tool for As (a) Bangladesh drinking water standard and (b) WHO guideline value.

target off-white sands for the installation of 33 safe drinking water wells, among which 25 (76%) were successful compared to BDWS. This evidence may be considered as a limitation to target off-white aquifers, specially the problem of identification of the targeted color when day light is a factor.

5. Conclusions

Sediment color and their relation to arsenic concentration in respective water are validated from a three year (pre- and post-monsoon) monitoring carried out in an extensive area and at different depths targeting aquifers of four colors which are also different in terms of redox characteristics. The validation of driller's perception on sediment colors led to the development of a simplified sediment color tool which provides an idea on the possible color shades under each of the four major colors black, white, off-white and red. This tool is user friendly and through the use of this tool it would be easy to target red colored sands for the installation of As-safe tubewells. Similarly, black colored sands must be avoided. Off-white sands could also be targeted as they give similar result as red sediments, but identification of off-white could be difficult in some cases which are considered as a factor of risk or uncertainty. White sands are seldom encountered at shallow depths and of less concern for shallow tubewell installation.

This study shows the potential for educating local drillers to target safe aquifers on the basis of the color characteristics of the sediments, which might be replicable to obtain arsenic safe water in many areas of Bangladesh and elsewhere in the world having similar geological environment characterized mainly by deltaic/alluvial sediments. Practically, if the local drillers can target safe aquifers based on this sediment color tool, it will play a significant role in As mitigation where the practice of using tubewell is well established and the local drillers are the main driving force in tubewell installation.

Conflict of interest

This study has been done under the research component of Sustainable Arsenic Mitigation (SASMIT) project of KTH Royal Institute of Technology, Sweden in collaboration with Dhaka University, Bangladesh, NGO Forum for Public Health in Bangladesh and Ramböll in Sweden.

To the best of our knowledge and belief, we have no conflict of interest in this study.

Acknowledgments

The authors thankfully acknowledge the Swedish International Development Cooperation Agency (Sida) for the financial support through the Contribution 75000854. We are thankful to Ann Fylkner, Monica Löwen and Bertil Nilsson from the Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology, Stockholm and Dr. Magnus Mörth from the Department of Geological Sciences, Stockholm University, for laboratory analyses. We gratefully acknowledge the supports provided by the professionals of the SASMIT project who were involved in this work in different capacities and contributed to this study. They are Marina Rahman, Rofi Uddin, Jahid Alam, Aminul Hoque, Samrat Alam, Ratnajit Saha, Biswajit Chakraborty, Rajib Hassan Mozumder, Rashedul Hasan and Nazhat Shirin Rashid. Cooperation extended by Ashis Biswas and Md. Annaduzzaman of KTH-International Arsenic Research Group is also acknowledged. We greatly acknowledge the participation and contributions of local drillers of Matlab, specially Md. Omar Faruk, Jahangir Prodhaniya, Chan Mia, Jahangir Bepari and Lokman. We must acknowledge many people who live in Matlab for extending their cordial cooperation during water sampling.

References

Ahmed KM, Bhattacharya P, Hasan MA, Akhter SH, Alam SM, Bhuyian MA, et al. Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: an overview. Appl Geochem 2004;19(2):181–200.

Ahmed MF, Ahuja S, Alauddin M, Hug SJ, Lloyd JR, Pfaff A, et al. Ensuring safe drinking water in Bangladesh. Science 2006;314:1687–8.

Argos M, Kalra T, Rathouz PJ, Chen Y, Pierce B, Parvez F, et al. Arsenic exposure from drinking water, and all-cause and chronic-disease mortalities in Bangladesh (HEALS): a prospective cohort study. Lancet 2010. http://dx.doi.org/10.1016/S0140-6736(10)60481-3.

Bakr MA. Quaternary geomorphic evolution of the Brahmanbaria–Noakhali Area, Comilla and Noakhali District, Bangladesh. Records of the geological survey of Bangladesh; 1977.

BGS, DPHE. Groundwater studies for arsenic contamination in Bangladesh. Final report, rapid investigation phase. Department of Public Health, Government of Bangladesh, Mott MacDonald and British Geological Survey; 1999.

BGS, DPHE. Arsenic contamination of groundwater in Bangladesh. In: Kinniburgh DG, Smedley PL, editors. Final report. BGS Tech. Rep. WC/00/19 Keyworth: British Geological Survey; 2001. [267 pp.].

Bhattacharya P, Chatterjee D, Jacks G. Occurrence of arsenic-contaminated groundwater in alluvial aquifers from delta plains, Eastern India: options for safe drinking water supply. J Water Res Dev 1997;13:79–92.

Bhattacharya P, Jacks G, Ahmed KM, Routh J, Khan AA. Arsenic in groundwater of the Bengal delta plain aquifers in Bangladesh. Bull Environ Contam Toxicol 2002;69:538–45.

Biswas A, Nath B, Bhattacharya P, Halder D, Kundu AK, Mandal U, et al. Testing tubewell platform color as a rapid screening tool for arsenic and manganese in drinking water wells. Environ Sci Technol 2012a;46:434–40.

Biswas A, Bhattacharya P, Mukherjee A, Nath B, Alexanderson H, Kundu AK, et al. Shallow hydrostratigraphy in an arsenic affected region of Bengal Basin: Implication for targeting safe aquifers for drinking water supply. Sci Total Environ 2014;485–486: 12–22. http://dx.doi.org/10.1016/j.scitotenv.2014.03.045.

Biswas A, Nath B, Bhattacharya P, Halder D, Kundu AK, Mandal U, et al. Hydrogeochemical contrast between brown and grey sand aquifers in shallow depth of Bengal Basin: consequences for sustainable drinking water supply. Sci Total Environ 2012b;431:402–12.

Bundschuh J, Litter M, Bhattacharya P. Targeting arsenic-safe aquifers for drinking water supplies. Environ Geochem Health 2010;32:307–15.

Charlet L, Chakraborty S, Appelo CAJ, Roman-Ross G, Nath B, Ansari AA, et al. Chemodynamics of an As “hotspot” in a West Bengal aquifer: a field and reactive transport modeling study. Appl Geochem 2007;22:1273–92.

Datta S, Neal AW, Mohajerin TJ, Ocheltree T, Rosenheim BE, White CD, et al. Perennial ponds are not an important source of water or dissolved organic matter to groundwaters with high arsenic concentrations in West Bengal, India. Geophys Res Lett 2011;38:L20404. http://dx.doi.org/10.1029/2011GL049301.

Harvey CF, Swartz CH, Badruzzaman ABM, Keon-Blute N, Yu W, Ali MA, et al. Arsenic mobility and groundwater extraction in Bangladesh. Science 2002;298:1602–6.

Hossain M, Islam MM, Rashid SMA, Rahman MM, Rahman M, Sultana S, et al. Delimiting the shallow aquifer characteristics using vertical electrical soundings (VES) and hydrochemical variability in a region with high arsenic groundwater in southeastern Bangladesh. In: Jean J-S, Bhattacharya P, Bundschuh J, editors. Arsenic in geosphere and human diseasesTaylor and Francis: CRC Press; 2010a. p. 105–7.

Hossain M, Bhattacharya P, Ahmed KM, Hasan MA, von Brömssen M, Islam M, et al. Sustainable Arsenic Mitigation (SASMIT): an approach for developing a color based tool for targeting arsenic-safe aquifers for drinking water supply. In: Bhattacharya P, Rosborg I, Sandhi A, Hayes C, Benoliel MJ, editors. Metals and related substances in drinking water cost action 637 — Proceedings 4th International Conference METEAU, Kristianstad, Sweden; 2010b. p. 272–6.

Hossain M, Bhattacharya P, Rofiuddin M, Rahman M, Jacks G, von Brömssen M, et al. Social perspective of arsenic mitigation and viability of various safe water options in Matlab, Southeastern Bangladesh. Geol Soc Am 2011;43(5):340. [Abstracts with Programs].

Hossain M, Bhattacharya P, Rahman M, Ahmed KM, Hasan MA, von Brömssen M, et al. A strategic approach to scale-up safe water access considering hydrogeological suitability and using social aspects in Matlab, Southeastern Bangladesh. Geol Soc Am 2012;44(7):156. [Abstracts with Programs].

Hossain M, Islam MM, Rahman M, Jacks G, Bhattacharya P, Alam MS, et al. A sediment color based tool for the installation of arsenic-safe drinking water tubewells in shallow aquifers in Bangladesh. Geol Soc Am 2013;45(7). [Abstracts with Programs].

Hug SJ, Gaertner D, Roberts LC, Schirmer M, Ruettimann T, Rosenberg TM, et al. Avoiding high concentrations of arsenic, manganese and salinity in deep tubewells in Munshiganj District, Bangladesh. Appl Geochem 2011;26(7):1077–85.

Inauen J, Hossain MM, Johnston RB, Mosler HJ. Acceptance and use of eight arsenic safe drinking water options in Bangladesh. PLoS One 2013;8(1):e53640. http://dx.doi.org/10.1371/journal.pone.005360.

Islam FS, Gault AG, Boothman C, Polya DA, Charnock JM, Chatterjee D, et al. Role of metal reducing bacteria in arsenic release in Bengal Delta sediments. Nature 2004;430:68–71.

Jakariya M, Rahman M, Chowdhury AMR, Rahman M, Yunus M, Bhuiya MA, et al. Sustainable safe water options in Bangladesh: experiences from the Arsenic Project at Matlab (AsMat). In: Bundschuh J, Bhattacharya P, Chandrasekharam D, editors. Natural arsenic in groundwater: occurrence, remediation and management. London: Balkema; 2005. p. 319–30.

Jakariya M, von Brömssen M, Jacks G, Chowdhury AMR, Ahmed KM, Bhattacharya P. Searching for sustainable arsenic mitigation strategy in Bangladesh: experiences from two Upazilas. Int J Environ Pollut 2007;31(374):415–30.

Jonsson L, Lundell L. Targeting safe aquifers in regions with arsenic-rich groundwaters in Bangladesh. Case study in Matlab Upazila, minor field studies, vol. 277Uppsala: Swedish University of Agricultural Sciences; 2004.

Lowers HA, Breit GN, Foster AL, Whitney J, Yount J, Uddin MN, et al. Arsenic incorporation into authigenic pyrite, Bengal Basin sediment, Bangladesh. Geochim Coschim Acta 2007;71:2699–717.

McArthur JM, Banerjee DM, Hudson-Edwards KA, Mishra R, Purohit R, Ravenscroft P, et al. Natural organic matter in sedimentary basins and its relation to arsenic in anoxic ground water: the example of West Bengal and its worldwide implications. Appl Geochem 2004;19:1255–93.

Morgan JP, McIntire WG. Quaternary geology of the Bengal Basin, East Pakistan and India. Geol Soc Am Bull 1959;70:319–42.

Mukherjee AB, Bhattacharya P. Arsenic in groundwater in the Bengal Delta Plain: slow poisoning in Bangladesh. Environ Rev 2001;9(3):189–220.

Mukherjee A, Fryar AE, Scanlon BR, Bhattacharya P, Bhattacharya A. Elevated arsenic in deeper groundwater of the western Bengal basin, India: extent and controls from regional to local scale. Appl Geochem 2011;26:600–13.

Munsell Color x-rite. Munsell soil-color charts with genuine Munsell color chips; 2009 [Year Revised, 2009; Munsell Color 4300 44th Street, Grand Rapids, MI 49512, USA].

Nath B, Berner Z, Chatterjee D, Basu Mallik S, Stüeben D. Mobility of arsenic in West Bengal aquifer conducting low and high groundwater arsenic. Part II: comparative geochemical profile and leaching study. Appl Geochem 2008;23:996–1011.

Nath B, Chakraborty S, Burnol A, Stüben D, Chatterjee D, Charlet L. Mobility of arsenic in the sub-surface environment: an integrated hydrogeochemical study and sorption model of the sandy aquifer materials. J Hydrol 2009;364:236–48.

Nickson R, McArthur J, Burgess W, Ahmed KM, Ravenscroft P, Rahman M. Arsenic poisoning of Bangladesh groundwater. Nature 1998;395:338.

Pal T, Mukherjee PK. ‘Orange sand’—a geological solution for arsenic pollution in Bengal delta. Curr Sci 2008;94(1):31–3.

Pal T, Mukherjee PK. Study of subsurface geology in locating arsenic-free groundwater in Bengal delta, West Bengal, India. Environ Geol 2009;56(6):1211–25.

Polizzotto ML, Kocar BD, Benner SG, Sampson M, Fendorf S. Near-surface wetland sediments as a source of arsenic release to ground water in Asia. Nature 2008;454:505–9.

Polya D, Charlet L. Rising arsenic risk? Nat Geosci 2009;2:383–4.

Robinson C, von Brömssen M, Bhattacharya P, Häller S, Bivén A, Hossain M, et al. Dynamics of arsenic in the oxidized aquifers in Matlab Upazila, Bangladesh: insight from experimental studies on sorption characteristics. Appl Geochem 2011;26:624–35.

SASMIT Annual Report. Sustainable Arsenic Mitigation (SASMIT) — community driven initiatives to target arsenic safe groundwater as sustainable mitigation strategy (Sida Contribution No.:73000854). 3rd Year Annual Report (April 2010–March 2011). Stockholm, Sweden: KTH-International Groundwater Arsenic Research Group, Department of Sustainable Development, Environmental Science and Engineering, KTH Royal Institute of Technology; 2011. [82 pp.].

Saunders JA, Lee M-K, Uddin A, Mohammad S, Wilkin R, Fayek M, et al. Natural arsenic contamination of Holocene alluvial aquifers by linked tectonic, weathering, and microbial processes: geochemistry. Geophys Geosyst 2005;6:Q04006. http://dx.doi.org/10.1029/2004GC000803.

Steer L, Evans A. Bangladesh's progress in health: healthy partnerships and effective pro-poor targeting. Overseas Development Institute, London UK: Development Progress, ODI Publications; 2011 [31 pp.].

Stollenwerk KG, Breit GN, Welch AH, Yount JC, Whitney JW, Forster AL, et al. Arsenic attenuation by oxidized sediments in Bangladesh. Sci Total Environ 2007;379:133–50.

van Geen A, Zheng Y, Versteeg R, Stute M, Horneman A, Dhar RK, Steckler R, Gelman M, Small C, Ahsan H. Spatial variability of arsenic in 6000 tubewells in a 25 km^2 area of Bangladesh. Water Resour Res 2003;39:1140.

van Geen A, Rose J, Thoral S, Garnier JM, Zheng Y, Bottero JY. Decoupling of As and Fe release to Bangladesh groundwater under reducing conditions. Part II: evidence from sediment incubations. Geochim Cosmochim Acta 2004;68:3475–86.

von Brömssen M, Jakariya M, Bhattacharya P, Ahmed KM, Hasan MA, Sracek O, et al. Targeting low-arsenic aquifers in groundwater of Matlab Upazila, Southeastern Bangladesh. Sci Total Environ 2007;379:121–32.