

Groundwater arsenic contamination from parts of the Ghaghara Basin, India: influence of fluvial geomorphology and Quaternary morphostratigraphy

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Abstract A groundwater arsenic (As) distribution in Faizabad, Gonda, and Basti districts of Uttar Pradesh is shown in the entrenched channels and floodplains of the Ghaghara River. Tubewell water samples were analysed for As through flow injection hydride generation atomic absorption spectrometry (FI-HG-AAS) system. About 38, 61, and 42 % of tubewells in Faizabad, Gonda, and Basti districts, respectively, have As >10 µg/l (WHO guideline). Moreover, 15, 45, and 26 % of tubewells in Faizabad, Gonda, and Basti districts, respectively, have As above 50 µg/l. About 86, 69, and 35 % of tubewells in Faizabad, Gonda, and Basti districts, respectively, are from shallow depth (21–45 m), and it is worth noticing that 47 % As-contaminated (As >10 µg/l) tubewells in these three districts are located within the depth of 10–35 m in Holocene Newer Alluvium aquifers. The high content of As (7.11 mg/kg) is measured in suspended river sediments of the Ghaghara River. Most of the As-contaminated villages in the Ghaghara Basin are located close to abandoned or present meander channels and floodplains of the Ghaghara River. In contrast, tubewells in Faizabad, Ayodhya, and Nawabganj towns are As-safe because of their positions on the Pleistocene Older Alluvium upland surfaces. Quaternary geomorphology plays an important role in groundwater arsenic contamination in the Ghaghara Basin. The sources of groundwater arsenic are geogenic and perennial mountainous rivers in the Ghaghara Basin supplied high sediment loads. The arsenic in groundwater of Ghaghara Basin is getting released from associated sediments which

were likely deposited from the Himalayas. The process of release of groundwater arsenic is reductive dissolution of iron hydroxides.

Keywords Groundwater arsenic · Ghaghara Basin · Older alluvium · Holocene aquifer · Geomorphology

Introduction

Arsenic (As) is found in soil and groundwater by natural and anthropogenic sources. High concentrations of As is one of the most hazardous chemical elements in drinking water in several parts of the world. Millions of tubewells in the Ganges–Brahmaputra–Meghna (GBM) delta plain are As-contaminated in the groundwater (Ravenscroft et al. 2009). Although the major switch from polluted surface water to groundwater in early 1970s helped people to avoid waterborne diseases, but naturally occurring high concentration of dissolved As in groundwater of alluvial aquifers has been causing serious health problems in millions of people for the last three decades. The upper permissible limit of As in drinking water is 10 µg/l in WHO guideline (WHO 1993) which has been endorsed by Bureau of Indian Standards (BIS 2003). The mode of occurrence, origin, and mobility of As in sedimentary aquifers in the Bengal Delta and other fluvial-deltaic setting in different parts of the world are mainly influenced by local geology, geomorphology, hydrogeology, and geochemistry of sediments and water, as well as anthropogenic activities (Nickson et al. 1998; Acharyya et al. 2000; Kinnibugh and Smedley 2001). The worst As-affected regions in Asia are mainly Bangladesh and West Bengal in India (Dhar et al. 1997; Nickson et al. 1998; Acharyya et al. 2000; Kinnibugh and Smedley 2001; Acharyya and Shah 2007, 2010; von

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Brömssen et al. 2007; Ravenscroft et al. 2009; Shamsud-duha et al. 2008). Arsenic pollution in groundwater is also reported from South, West and East Asia viz., Pakistan, People Republic of China, Taiwan, Vietnam, Laos and Cambodia, Nepal, Egypt and Yemen (Tseng et al. 2000; Berg et al. 2001; Mondal and Suzuki 2002; Nickson et al. 2005; Gurung et al. 2005; Al-Mikhlaifi 2010; Kashouty et al. 2012).

Recently, groundwater As contamination has been reported from the Middle Ganga Plain in the states of Jharkhand, Bihar, and Uttar Pradesh (Chakraborty et al. 2003; Bhattacharjee et al. 2005; Shah 2008). The Ghaghara River is a distributary of the River Ganges and is a significant river in UP with many cities, towns and villages are located on its bank (Fig. 1). This study is undertaken for groundwater As distribution in Faizabad, Gonda, and Basti districts of Uttar Pradesh involving tubewells within Holocene Newer Alluvium aquifers, as well as, Pleistocene Older Alluvium aquifers. The main objective of the study is to investigate the distribution of groundwater As in entrenched channels and floodplains of the Ghaghara River under Quaternary geomorphological setting (Fig. 2).

Study area

The Ghaghara River has originated from Matsatung glacier in the Himalayas near Mansarovar Lake in Tibet and traveled a distance of about 1080 km in NW–SE direction,

to join the Ganga River. The Ghaghara River adopts a meandering path through the alluvial plains, frequently shifting their courses and forming ox-bow lakes. The topography of the area is heterogeneous; varying between upland surfaces, plain areas and low-lying small natural bodies, viz., swamp and ponds. The Older Alluvium is located at an elevation of 10–20 m above the river level and constitutes the higher interfluvial areas. The Pleistocene Older Alluvium surfaces in the Ghaghara Basin are characterized by yellow–brown coloured sediments with profuse calcareous and ferruginous concretions (Fig. 3). Newer Alluvium forms the river valley terrace and is located at an elevation of 5–10 m above river level. The Holocene Newer Alluvium surfaces are recognized by grey to black coloured organic-rich argillaceous sediments in entrenched channels and floodplains of the Ghaghara River (Fig. 3). The area is under humid subtropical climate and the annual average rainfall is 1041 mm. Temperature ranges between maximum (47 °C) in summer and minimum (2 °C) in winter.

The distribution of groundwater As in the Ghaghara Basin is prepared based on the Survey of India topographic sheets (63J/1, J/2, J/5, and J/6) in 1:50,000 scale, with field checks to identify fluvial landforms and soil characters. The study areas in Faizabad, Gonda, and Basti districts along entrenched channels and floodplains of the Ghaghara River are shown in Fig. 2. In this study, approximately 1500 km² areas have been mapped to delineate groundwater As-contaminated and As-safe areas.

Fig. 1 Quaternary sediments in the Indo-Ganga Basin and Bengal Basin. The study area in the Ghaghara Basin is shown in Fig. 2. A Allahabad, V Varanasi, BX Buxar, B Ballia, C Chappra, P Patna, BG Bhagalpur

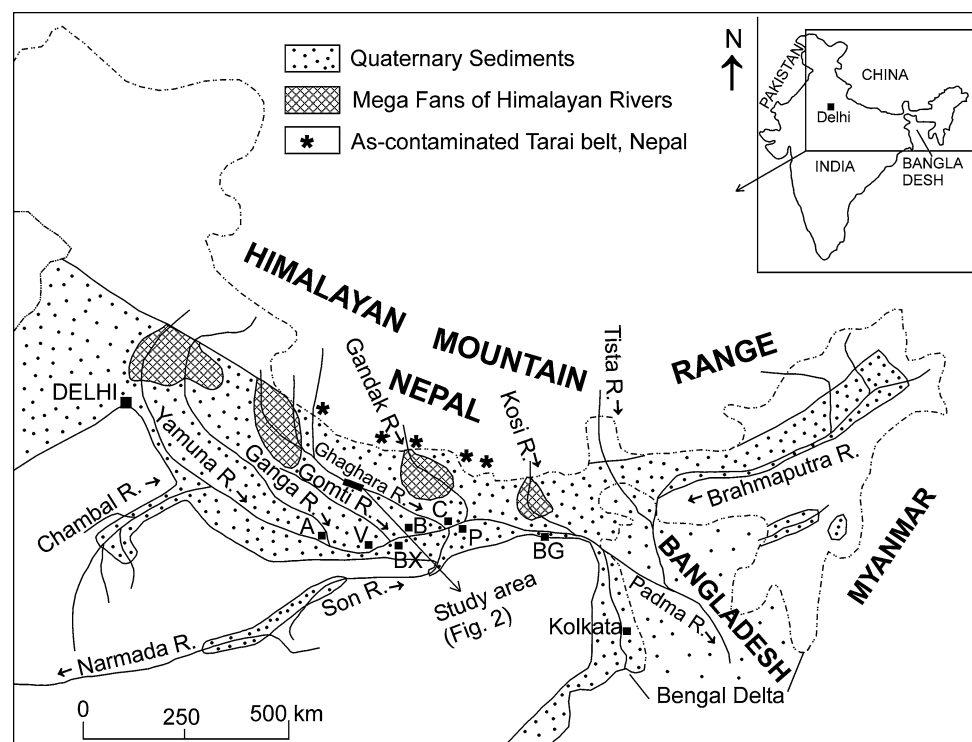


Fig. 2 Groundwater arsenic distribution in Faizabad, Gonda, and Basti districts of Uttar Pradesh

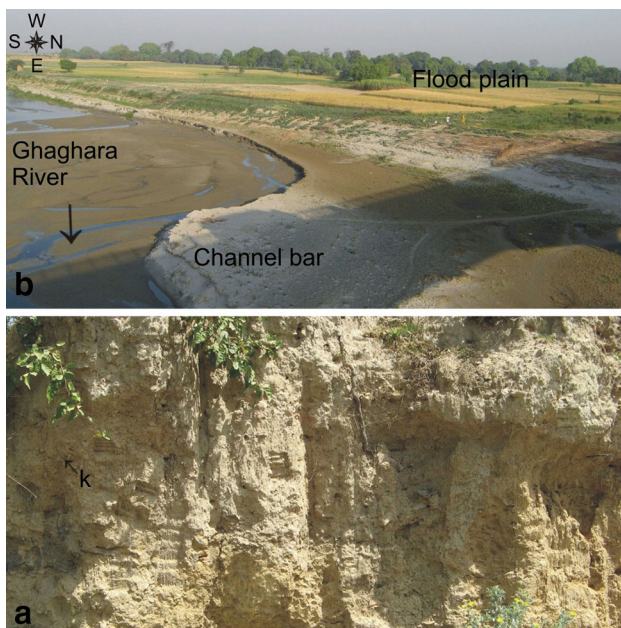
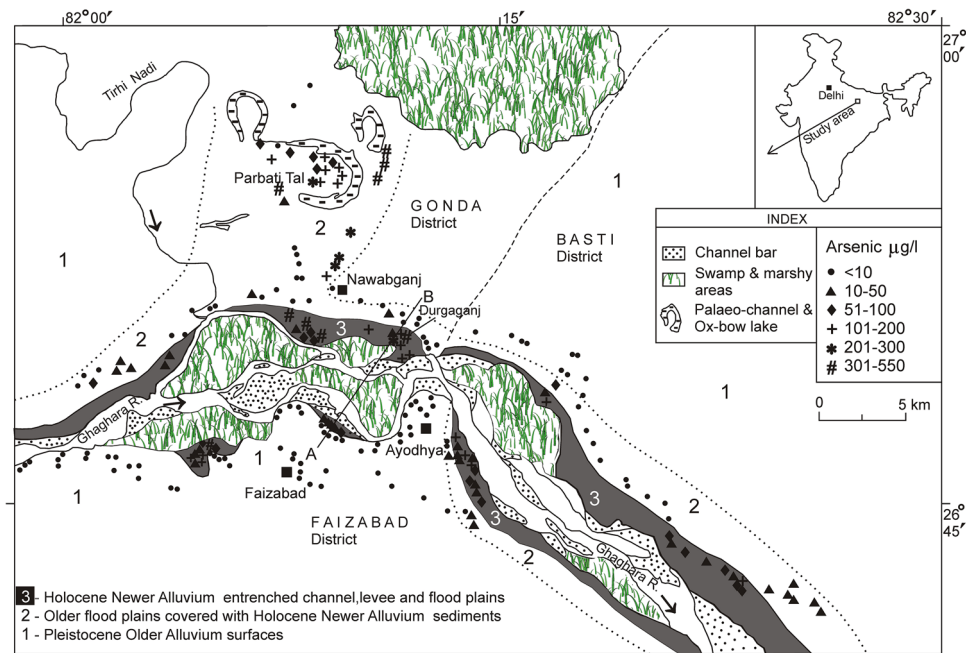


Fig. 3 Pleistocene Older Alluvium sediments (a) with calcareous and ferruginous concretion (*k*) in Faizabad areas. Entrenched channels and floodplains of the Ghaghara River (b)

Geological setting

The Quaternary geology of the Indo-Gangetic plains has been subdivided the sediments into Older Alluvium and Newer Alluvium (Pascoe 1964). This classification was revised by Pathak et al. (1978) as Upper Siwalik (Upper Pliocene to Lower Pleistocene), Older Alluvium (Middle to Upper Pleistocene), and Newer Alluvium (Upper

Pleistocene to Recent) in order of superposition. The Siwalik Supergroup is further subdivided into Lower, Middle, and Upper groups ranging in age from Middle Miocene to Early Pleistocene in northern part of the Siwalik Basin forming the Outer Himalaya. The Banda Group in the southern part of the basin corresponds to the Upper Siwalik (Kumar et al. 1996).

The sediments formed Banda Older Alluvium which is characterized by variegated clays followed by the clastic sediments. However, the sediments derived from the Himalayas in northern part of the basin constitute the Upper Siwalik (Dwivedi et al. 1997).

The Ghaghara Valley in the Ganga Plain consists of thick pile of Quaternary sediments. Geomorphologically, the Older Alluvium surfaces, i.e. the Varanasi Older Alluvium constitute upland surfaces which are also recognized as the *Bhangar* surface and are occupying a major part of the area. The Varanasi Older Alluvium consists dominantly of multiple fill polycyclic sequence of sand, silt, and clay (Kumar et al. 1996). In the Ghaghara Basin, the top 3 m part is of silt–clay facies corresponding to suspension load of floodplain environment underlain by arenaceous facies corresponding to channel fill palaeoenvironment. The subsurface boreholes down to a depth of 300 m record a number of calcrete (*kankar*) and argillaceous bands at various levels (Dwivedi et al. 1997).

The river Ghaghara draining the area has developed a second geomorphic unit, the low-lying floodplains—the *Khadar* surface of the river. The main geomorphic features are giant channel bar, natural levee, and floodplains. The Holocene Newer Alluvium comprises grey to black

coloured organic-rich argillaceous sediments in entrenched channels and floodplains of the Ghaghara River. The top thin layer of silt–clay has been deposited in a lacustrine condition towards the close of sedimentation. The landscape of the study area is typically fluvial, characterized mainly by active channels, abandoned channels, natural levees, back swamps, and floodplains. The Quaternary lithostratigraphy in the Ghaghara Basin has been classified broadly into two units, i.e. Older Alluvium and Newer Alluvium (Table 1).

The subsurface aquifer system in the area is known from the study of Central Ground Water Board (CGWB) exploratory well data. Groundwater occurs in pore spaces of the unconsolidated alluvial sediment in the zone of saturation. The groundwater in the area occurs both under confined and water table conditions. The area is underlain by the pile of unconsolidated Quaternary alluvium consisting of clays, silt, occasional calcrete (*kankar*), sand of various grades, and gravels in different proportions. The pre-monsoon depth to water level ranges from 2.46 to 6.48 mbgl, whereas in post-monsoon depth to water level varies from 1.12 to 5.6 mbgl. Sediment from ground level varies from 15 to 20 m, comprises fine to medium grained sand with thin clay at top. Water level varies from 2.45 to 7.80 mbgl and the depth of dug wells varies from 3.60 to 12.50 mbgl (Srivastava 2009).

Materials and methods

About 80 tubewell water samples were tested on spot through EZ As Test Kit, Hach, USA (Cat No. 28228-00) in Faizabad, Gonda, and Basti districts of Uttar Pradesh. The

minimum determination limit of Kit is 10 µg/l. Kit data was used as a guide to delineate As-contaminated and As-safe areas in the field. In this study, 231 tubewell water samples from the above districts were tested in the laboratory.

The geographic location of each tubewell was recorded by a global positioning system (Garmin eTrex Vista), and the depth of the tubewell was acquired through personal communication with tubewell owners. The results of As concentrations in tubewells is shown in Table 2, and the GPS location of each tubewell is marked in the toposheet to prepare As distribution map in entrenched channels and floodplains of the Ghaghara River (Fig. 2).

Hand tubewell water samples were collected in acid prewashed 10 ml plastic bottles. Immediately after collection, one drop of dilute nitric acid (1:1) GR Grade was added as preservative. All reagents were of Analar grade. A solution of 2 % NaBH₄ (Merck, Schuchardt, Germany) was prepared in 0.5 % NaOH (Merck, Bombay, India). A 5.0 M solution of HCl (Merck, Bombay, India) was used. All these solutions were prepared using distilled de-ionised water. The flow rate for both tetrahydroborate and hydrochloride acid was 1 ml/min. Blank was prepared and measured under the same conditions. The tubewell water samples were analysed for As following a flow injection hydride generation atomic absorption spectrometry (FI-HG-AAS) system. Model Analyst-700 spectrometer with As lamp (lamp current 380 mA), illuminating at 193.7 Å (specific for As) was utilized for this purpose (Biswas et al. 2008).

Four sediment core samples from the borehole in Duraganj Village (26°49.128':82°11.834') were collected through hand-flapper boring. One sediment sample of

Table 1 Lithostratigraphy and morphostratigraphy in the Ghaghara Basin, Uttar Pradesh

Age	Lithostratigraphy		Morphostratigraphy	
	Lithounits	Lithology	Morphounits	Landform
Holocene				
Newer	Recent Alluvium	Grey, fine, micaceous sand and silt (4–8 m)	i. Swamps ii. Flood plain (<i>Khadar</i> surface)	Abandoned channels/ lakes
Alluvium	Ghaghara Terrace Alluvium	Top clay, grey fine to medium grained micaceous sand and sandy silt (9–20 m)	i. Ghaghara older flood plains ii. Ghaghara erosional terrace	Point and channel bars, meander cut-offs abandoned channels
Disconformity				
Mid to Late Pleistocene	Varanasi Older Alluvium	Polycyclic sequence of brownish yellow oxidized sand, silt and clay with calcrete (<i>kankar</i>). Argillaceous facies dominates in the upper part and arenaceous in the lower part (+300 m)	Varanasi Older Alluvium plain (<i>Bhangar</i> surface)	Palaeochannels
Pre-Quaternary concealed basement rocks				

Table 2 Tubewell As ($\mu\text{g/l}$) distribution in percentage in the Ghaghara Basin, Uttar Pradesh

Study area	>10	>50	>100	>200	>300	Max. As
Faizabad district ($N = 101$)	38	15	9	5	2	350
Gonda district ($N = 88$)	61	45	33	25	18	510
Basti district ($N = 42$)	42	26	2	–	–	150

approximately 20 g clayey sand from the depth of 23 m was taken in this study and the sample was dried in an oven at about 50 °C for approximately 24 h. Sediment sample was ground homogeneously and crushed with a mortar and pestle. Sample weighing 0.5 g was taken in Teflon bomb, and 2 ml nitric acid was added with it. It was digested at 120 °C temperature for 8 h in hot air oven. Subsequently, vessel was emptied in a beaker and the sample evaporated near to dryness. The 5 ml distilled de-ionised water was added to the digested sample, and it was filtered through 0.45 μ Millipore filter. During analysis 5 ml acidified sample was added with 10 ml buffer, 5 ml hydroxylamine hydrochloride, and 2.5 ml phenanthroline, and a final volume of 25 ml was prepared. The prepared solution was used for As and iron analysis. Iron was analysed by 1,10-phenanthroline method by the use of UV spectrophotometer.

The accuracy of analytical method using FI-HG-AAS was verified by analysing standard reference sample of water (quality control sample for trace metal analysis) (certified value $17.6 \pm 2.21 \mu\text{g/l}$) from the US Environmental Protection Agency, Environmental monitoring and support laboratory, Cincinnati, Ohio, USA and certified reference material BND 301 (certified value $990 \pm 200 \mu\text{g/l}$), from the National Physical Laboratory, New Delhi, India.

Results

Arsenic contamination in tubewell water in Faizabad, Gonda, and Basti districts along the Ghaghara River have been observed in significant amount. About 38 % of tubewells in Faizabad district, 61 % of tubewells in Gonda district, and 42 % of tubewells in Basti district have As $>10 \mu\text{g/l}$ (WHO guideline). Moreover, 15 % of tubewells in Faizabad district, 45 % of tubewells in Gonda district, and 26 % of tubewells in Basti district have As above 50 $\mu\text{g/l}$ (Table 2).

Maximum concentrations of As in tubewells from Faizabad, Gonda, and Basti districts are 350, 510, and 150 $\mu\text{g/l}$, respectively. The density of As-contaminated tubewells in Gonda districts is higher compared to that of the Faizabad and Basti districts, and even 25 % of

tubewells in Gonda district reveal occurrence of As above 200 $\mu\text{g/l}$ (Table 2). Groundwater As distributions in entrenched channels and floodplains of the Ghaghara River are divided into three parts viz., (1) Pleistocene Older Alluvial uplands surfaces, i.e. Varanasi Older Alluvium with oxidized to yellow–brown coloured sediments, and aquifers are As-safe in groundwater, (2) narrow belts of older floodplains covered with Holocene sediments on top, and aquifers are locally As-contaminated, and (3) Holocene to recent entrenched channels and floodplains of the Ghaghara River and tubewells are highly As-contaminated in groundwater (Fig. 2). Maximum level of As in tubewell is 510 $\mu\text{g/l}$ from Bakir Mahangopur Village ($26^{\circ}51.559':82^{\circ}47.669'$) of Nawabganj block.

The subsurface information of tubewell has been collected from owners of the tubewells as well as from the local drillers and accordingly a profile section (A–B) is plotted (Fig. 4). The profile section shows that tubewells located in Holocene Newer Alluvium aquifers in the Faizabad side have As concentrations of 25, 23, and 72 $\mu\text{g/l}$ corresponding to the depth of 30, 37, and 12 m, respectively. Moreover, tubewells located in Holocene Newer Alluvium aquifers in the Durgaganj areas have As concentrations of 140, 125, and 410 $\mu\text{g/l}$ corresponding to the depth of 33, 33, and 10 m, respectively. However, As-safe tubewells ($<10 \mu\text{g/l}$) are mainly located in the Pleistocene Older Alluvium aquifers at the both end of Faizabad and Durgaganj areas (Fig. 4). Tubewells in Faizabad town is virtually free of As contamination ($<10 \mu\text{g/l}$) in

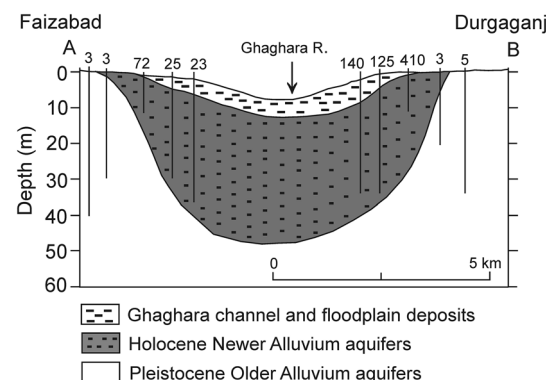


Fig. 4 A–B profile section is marked in Fig. 2. Arsenic value ($\mu\text{g/l}$) of each tubewell is marked its top

groundwater, as it is located on the Pleistocene Older Alluvium surfaces (Fig. 2).

Arsenic-contaminated areas in and around of Faizabad, Ayodhya, and Nawabganj towns are mainly confined in the meandering belt of the Ghaghara River. Durgaganj Village ($26^{\circ}49.786':82^{\circ}11.873'$) and Jayedpur Majha ($26^{\circ}49.786':82^{\circ}11.873'$) are located on the north bank of Ghaghara River where As concentrations in tubewells are 410 and 455 $\mu\text{g/l}$, respectively. These areas are in channels and flood plains of the Ghaghara River. However, opposite side of Durgaganj Village is Ayodhya town, and tubewells in Ayodhya town are As-safe in groundwater ($<10 \mu\text{g/l}$) because of their positions on Older Alluvium upland surfaces (Fig. 2). As-contaminated tubewells are also located on the older floodplains (zone 2) to the south-east of Ayodhya town near the bank of Ghaghara River. These areas are under shallow cover of Newer Alluvium Holocene sediments with As level $\leq 200 \mu\text{g/l}$. It may be noted that villages around Parbati Tal are As-affected in groundwater. These inundated areas consist of palaeochannels and ox-bow lakes of the Ghaghara River and its tributaries. Raghuraj Nagar Village ($26^{\circ}56.101':82^{\circ}10.969'$), although located in this area, shows maximum As concentration of 450 $\mu\text{g/l}$ (Fig. 2).

Faizabad and Ayodhya twin towns are historically famous places, and the disputed land of Babri Masjid and Ram Mandir issue has evoked international attention. The twin towns, on the southern bank of the Ghaghara River, are located on the yellow-brown coloured oxidized Pleistocene Older Alluvium upland surfaces with calcareous and ferruginous concretions (Fig. 5). Tubewells in twin towns are As-safe in groundwater. However, tubewells in outskirts of Faizabad town near Pathan Toli ($26^{\circ}47.136':82^{\circ}09.990'$) and Kala Majha ($26^{\circ}46.999':82^{\circ}04.627'$) have maximum As concentrations of 72 and 350 $\mu\text{g/l}$, respectively. About 47 % As-contaminated (As $>10 \mu\text{g/l}$) tubewells in these three districts are located within the depth of 10–35 m (Fig. 6).



Fig. 5 Faizabad and Ayodhya towns are located on the Older Alluvium upland surfaces and their opposite side is Newer Alluvium surfaces

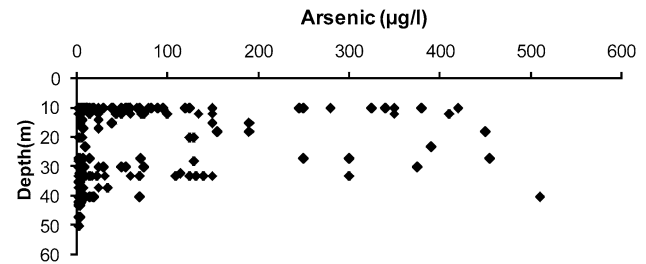


Fig. 6 Correlation between arsenic concentration and depth of tubewell in the Ghaghara Basin, Uttar Pradesh

The tubewells located in very shallow depth (10–20 m) in Faizabad, Gonda and Basti districts are 12, 31, and 62 %, respectively (Table 3). About 86, 69, and 35 % of tubewells in Faizabad, Gonda, and Basti districts, respectively, are within the depth of 21–45 m. Maximum As concentration of 510 $\mu\text{g/l}$ corresponds to a depth of 40 m, as observed in Bhakir Mahangopur Village ($25^{\circ}51.559':82^{\circ}07.669'$).

One 40 m hand-flapper borehole was done in As-affected Durgaganj Village ($26^{\circ}49.128':82^{\circ}11.834'$). The subsurface sediments from ground level are as follows: 3 m top soil, 3–8 m grey clay mixed with fine sand, 8–9 m grey clayey shale, 9–20 m fine to medium grained greyish white sand mixed with clay, 20–21 m grey clayey shale, 21–30 m medium to coarse grained greyish white sand, 30–31 m grey clayey shale, 31–40 m coarse grained greyish white sand, and below 40 m yellowish brown clay with calcrete.

The sediments collected from the borehole at Durgaganj Village ($26^{\circ}49.128':82^{\circ}11.834'$) are mainly Newer Alluvium. Arsenic and iron concentrations in clayey sand at Durgaganj Village are 6.19 mg/kg and 7.12 gm/kg, respectively. Moreover, As concentrations in tubewells in and around of that borehole are 140, 125, and 410 $\mu\text{g/l}$ (Fig. 2). It may be noted that the average As content in clayey sand is 12 mg/kg in Murshidabad district, and West Bengal (Acharyya et al. 2000). Arsenic and iron concentrations in clayey sand are 7.7 mg/kg and 4.26 gm/kg, respectively, in Manikganj district, Bangladesh (Sham-sudduha et al. 2008).

Discussion

Relation of groundwater arsenic with Quaternary geomorphology

The Quaternary sediments in the Indo-Ganga foredeep basin were deposited during Pleistocene period. Major deposit of sediments in the foreland basin has their source in the Himalayas under episodic tectonic activity and climate variability. However, minor inputs of sediments from

Table 3 Depth of tubewell in As-contaminated areas in the Ghaghara Basin, Uttar Pradesh

Study areas	Depth	Depth	Depth	Max. Depth (m)
	10–20 m (%)	21–45 m (%)	46–60 m (%)	
Faizabad district (<i>N</i> = 101)	12	86	2	60
Gonda district (<i>N</i> = 88)	31	69	–	43
Basti district (<i>N</i> = 42)	62	35	2	47

the Peninsular shield under cold, semiarid, and a warm humid palaeoclimatic conditions (Singh 2004). The Ganga Plain has developed a network of small drainages and entrenchment of the major rivers during ~20 to 13 ka BP. The network became dense during 13–8 ka BP (early Holocene). During 8–6 ka BP small drainages changed to large lakes and extensive deposition of sediment took place in the upland interfluvial surfaces. Most of the areas in the Ganga Plain are covered by 5–10 m thick muddy sediments, representing deposition during mid to late Holocene (Singh 2004).

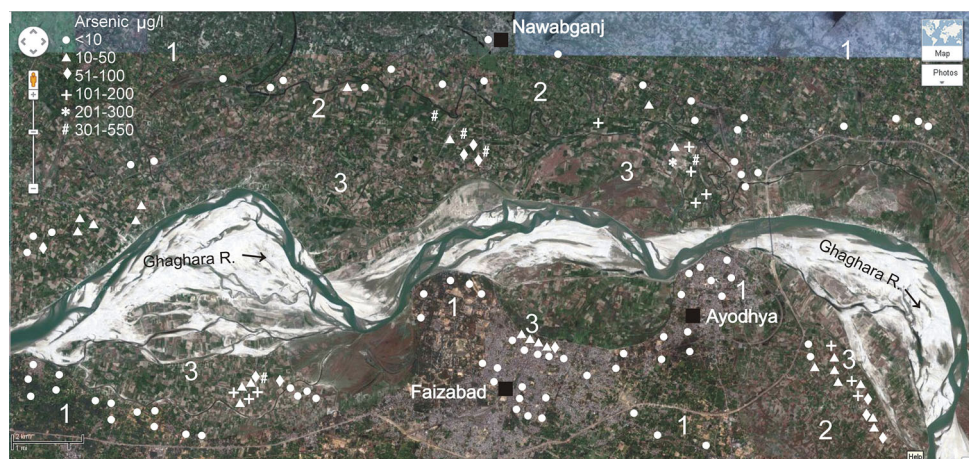
Arsenic-contaminated tubewell in and around of Faizabad, Ayodhya, and Nawabganj towns are shown in Google satellite imagery. Geomorphologically, the Ghaghara Basin is subdivided into three zones viz. (1) Pleistocene Older Alluvium upland surfaces, i.e. Varanasi Older Alluvium, (2) older floodplains covered with Holocene Newer Alluvium sediments on top, and (3) Holocene Newer Alluvium entrenched channels and floodplains of the Ghaghara River (Fig. 7). Tubewells in Pleistocene Older Alluvium aquifers are As-safe in groundwater, whereas tubewells located in entrenched channels and flood plains of Holocene Newer Alluvium aquifers are As-contaminated in groundwater. The latter occurs in proximity to meander or abandoned channels. It may be noted that high concentrations of groundwater As in alluvial aquifers in Bangladesh and West Bengal are reported in

different parts of Bengal Delta. Arsenic contamination in groundwater in Bengal Delta is controlled by regional geologic–geomorphic units of Older Alluvium and Younger Alluvium sediments (Acharyya et al. 2000; von Brömssen et al. 2007; Shamsudduha et al. 2008).

The major parts of the Ghaghara Basin consist of interfluvial upland surfaces of Older Alluvium. These Pleistocene Older Alluvium interfluvial upland surfaces are characterized by yellow–brown coloured sediments with profuse calcareous and ferruginous concretions, and are either exposed or occur under shallow cover of Holocene sediments. In this study, Faizabad, Ayodhya, and Nawabganj towns in the Ghaghara Basin are located on the Pleistocene Older Alluvium upland surfaces, i.e. Varanasi Older Alluvium, and tubewells are As-safe in groundwater. Moreover, Holocene Newer Alluvium aquifers are characterized by grey to black coloured organic-rich argillaceous sediments, and tubewells in Holocene aquifers are As-contaminated in groundwater (Fig. 4). This may be comparable with the Bengal delta where high concentrations of groundwater As is found in Holocene aquifers, while Pleistocene aquifers have a low As level (Raven-scroft et al. 2009).

Arsenic contamination in groundwater in the Ghaghara Basin is shown in the schematic 3D diagram (Fig. 8). Tubewells located in the entrenched channels and floodplains of the Ghaghara River are mostly As-contaminated. Moreover, tubewells located in Pleistocene Older Alluvium aquifers with thin cover of Holocene sediments on top are As-safe in groundwater. Arsenic affected tubewells are also locally observed in older floodplains covered with Holocene Newer Alluvium sediments on top. This model regarding groundwater As can be applied in others fluvial-deltaic setting in South and South-East Asia as well. Groundwater As is mostly found in the delta plains, modern floodplains, marshes, and depressed lowlands areas in Red River Delta and Bengal Delta (Berg et al. 2001; Kinnibugh and Smedley 2001). High As areas are mainly characterized by low

Fig. 7 Google satellite imagery showing distribution of arsenic-contaminated tubewells in entrenched channels and floodplains of the Ghaghara River



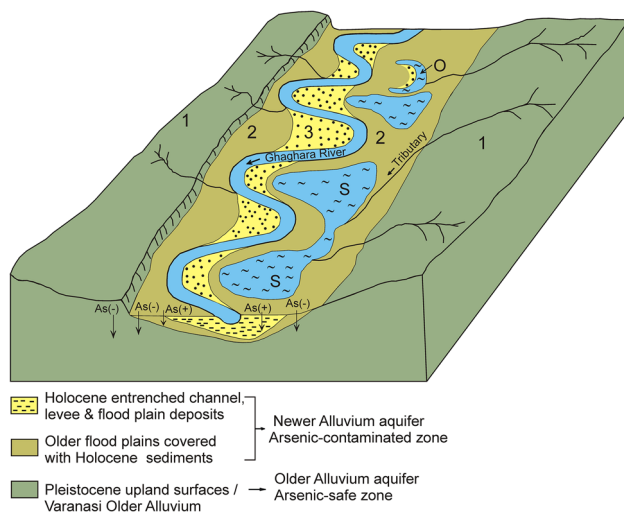


Fig. 8 Schematic 3D diagram showing groundwater arsenic status in Holocene and Pleistocene aquifers. *O*-Ox-bow lake, *S*-Back swamp, *As* (-) *As*-safe aquifers, *As* (+) *As*-contaminated aquifers

slopes in shallow aquifers where groundwater flow is mainly controlled by elevation and slope variations. Occurrences of high groundwater *As* are significantly linked with the Pleistocene and Holocene aquifers in the Red River Delta and Bengal Delta (Berg et al. 2001; Ravenscroft et al. 2009; Shamsudduha et al. 2008).

In the Ghaghara Basin, Pleistocene Older Alluvium yellow–brown coloured surfaces were subjected to erosion and oxidation, and were dissected by channels and floodplains and buried under younger Newer Alluvium sediments. These oxidizing Pleistocene upland surfaces were well flushed by groundwater flow due to high-hydraulic head and also devoid of organic matter. The environment of the oxidized Pleistocene Older Alluvium sediments is not favourable to release sorbed *As* to groundwater. However, deeper tubewells (>50 m) in Pleistocene Older Alluvium aquifers in the Ghaghara Basin would be a better option for *As*-safe groundwater.

Source of arsenic in the Ghaghara Basin

The Ghaghara Basin was formed due to accumulation of bulk sediments from the Himalayan hill range. There are several *As* bearing minerals deposits in the Himalayan hill range including hydrothermal pyrite-chalcopyrite-arsenopyrite-galena mineralization associated with quartz veins in Buniyal, Doda, Almora Garhwal, J and K Hills (Tewari and Gaur 1977). The Indus-Tsangpo suture in north India is marked by ophiolitic rocks, including olivine serpentinites. These ophiolites are composed of serpentinitized peridotite, layered mafic to ultramafic rock, volcanic and oceanic sediments that contain high *As* (Guillot and Charlet 2007).

Terai belt of Nepal is *As*-contaminated, and the Terai sediments have come from the Himalayan hill range (Gurung et al. 2005). Most of the rivers in northern parts of the Gangetic Plain have originated from the Himalayan hill range. The Ghaghara River, the focus of present work, has also originated from the Himalayas and flows through the Terai belt of Nepal. Arsenic in suspended river sediments of the Ghaghara River is 7.11 mg/kg during monsoon period (Shah 2014).

Conclusion

Hand tubewell in Faizabad, Gonda, and Basti districts of Uttar Pradesh are prone to *As* contamination in groundwater. These tubewells are located in entrenched channels and floodplains of the Ghaghara River. It is observed that *As*-affected villages are preferentially located close to abandoned or present meander channels of the Ghaghara River. Most of the *As*-contaminated tubewells are in the depth range of 20–40 m, which are located in Holocene Newer Alluvial aquifers. However, tubewells located on the Pleistocene Older Alluvium upland surfaces in Faizabad, Ayodhya, and Nawabganj towns are virtually *As*-safe in groundwater. The major parts of the Ghaghara Basin consist of upland oxidized Pleistocene yellow–brown coloured sediments. The environment of the Pleistocene Older Alluvium aquifers is not favourable to release *As* to groundwater, and aquifers are generally *As*-safe in groundwater. The Ghaghara River carries high content of *As* (7.11 mg/kg) in suspended river sediments. In *As*-contaminated areas, deeper tubewells (>50 m) in Pleistocene Older Alluvium aquifers are considered as better option for *As*-safe drinking water.

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