frequency. However, the IODMI of preceding months cannot provide indications of the tropical cyclone frequency during the pre-monsoon season.

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'Orange sand' – A geological solution for arsenic pollution in Bengal delta

Arsenic pollution in the Bengal delta is considered to be the most hazardous environmental problem in recent years, affecting millions of people residing in West Bengal, India and adjoining Bangladesh. Several studies have been carried out over the last few decades to address this problem. These studies were based on reports of arsenic incidences[1,2], genetic aspect of arsenic entrapment and its consequent release into groundwater[3,4]; some have come up with suggested measures mostly based on surface filtration of the contaminated water[5,6]. Tubewells in the depth range 20–50 m yield maximum arsenic concentration in groundwater; the values may exceed 500 ppb compared to the maximum permissible limit of 50 ppb in potable water[7,8]. On the basis of knowledge of low arsenic in deeper aquifers[9], tubewells were also made in the depth range 120–140 m. But in the affected areas[6], some of these (30–40%) are also found to yield arsenic greater than 50 ppb. Thus people are forced to use costly surface filters either at domestic level or community level. In the long run, majority of the filters are also found to be non-functional in reducing arsenic and people have no other alternative than to drink the contaminated water and consequently become a recurring victims of arsenic toxicity. The present work enumerates a geological solution for this pollution problem, simply by tapping groundwater from a specific aquifer which would yield arsenic-free groundwater.

The Bengal delta, covering the eastern part of West Bengal up to Bangladesh, represents the Quaternary deposit of the Ganga–Padma–Brahmaputra river system. The deposits are relatively younger compared to the deposit of Damodar flood plain in the western part of West Bengal or its equivalent in Bangladesh[10–12]. In the affected areas there are multiple aquifers at different depths; each is semiconfined to leaky-confined, or confined by a variety of overlying clays[13]. The clays vary from light grey to dark grey and soft to hard in nature, whereas the sands are mostly grey and fine-to-medium in size. Each sand–clay fining upward unit represents a single cycle of fluvial deposit, superposed on each other to form a stack of multiple aquifers. In the Bengal delta, groundwater is tapped by people from the leaky-confined, grey, fine sand in the depth range 20–50 m. Community wells are also made in these localities by the local administration, tapping groundwater from the deeper grey, fine sand aquifers in the depth range 60–140 m. The aquifers of grey, fine sand with an overlying grey, soft clay, enriched in organic matter occurring at different depths yield high arsenic in groundwater[14]; their regional extent along with depth consistency thus has resulted in severe geogenic health hazards of toxic arsenic in these areas.

The groundwater in Damodar flood plain is free from arsenic, except in a few localities[15]. The aquifer sand of this plain and its equivalent in Bangladesh[11,12] is yellowish-brown in colour and is known as orange sand. However, orange sand was not reported earlier within the younger

Figure 1. Stratigraphic position of orange sand unit yielding arsenic-free groundwater. This unit is sandwiched between the overlying and underlying grey sands, both yielding high levels of arsenic in groundwater.

Table 1. Characteristics of orange sand vis-à-vis grey sand in the Bengal delta

Type of sand	Nature of aquifer	Depth (m) bgl	Thickness (m)	Description	Significant minerals	Sediment arsenic (mg/kg)	Groundwater arsenic (ppb)
Orange sand	Confined	40–50	5–10	Orange, fine-to-medium sand grade to brownish-grey coarse sand at depth	Fe-oxyhydroxide-coated clastic grains, illite, siderite, etc.	12–16	1–10
Grey sand	Leaky-confined	3–140	3–45	Grey, fine-to-medium sand grade to coarse sand at depth	Muscovite, biotite, chlorite, etc.	5–15	50–700

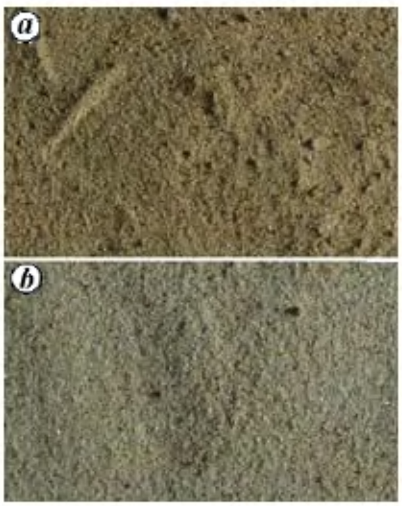

Figure 2. Characteristic-textural differences between (***a***) orange sand and (***b***) grey sand in aquifers of the Bengal delta.

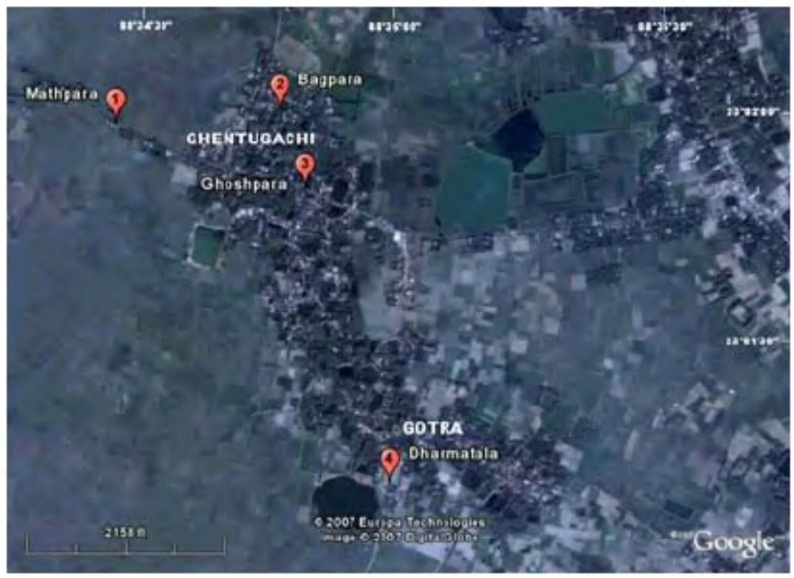

Figure 3. Satellite image of Ghentugachi and Gotra villages showing locations of four tubewells tapping arsenic-free groundwater from the orange sand horizon. All the four tubewells are placed at the convex tip of the abandoned channel (manifested by darker tone). The lighter tone at its eastern part indicates the later channel domain.

fluvial deposit of the Bengal delta. In parts of West Bengal, one hundred and forty coring and non-coring bore holes have been drilled from Baruipur in the south to Malda in the north, specifically through the younger fluvial deposit to decipher the characteristics of the subsurface sediments. The mineral constituents and their arsenic contents have already been reported[8,16–18]. It has been observed that some of the boreholes have intersected 5–10 m thick orange sand in the depth range 40–50 m, sandwiched between two grey sand-bearing aquifers containing high levels arsenic (Figure 1). This orange sand is immediately underlain by a brown to bluish-grey hard clay with little pore water. The formation of calcrete at the top and Fe-oxyhydroxide staining over the clastic grains indicate sub-aerial exposure for oxidation in a temporary, non-depositional set-up (hiatus), which also resulted in the development of yellowish-brown illite as well as siderite, thus making the entire sand yellowish-brown, designated here also as orange sand (Figure 2 *a*). In contrast, the younger fluvial deposit is characteristically grey to dark grey in colour and rich in organic matter. The fine-to-medium sand of this horizon is rich in biotite and muscovite, which along with higher concentration of organic matter make the sand glittering grey; sometimes it is referred to as 'silver sand' (Figure 2 *b*).

Ghentugachi and Gotra villages in Chakdah block, Nadia district, West Bengal are among the worst arsenic-affected blocks[8,19], where people are dying because of the menace. In these two villages four test tubewells are dug in the orange sand aquifer at Mathpara (23°01′53.1″ : 88°34′28.1″), Bagpara (23°01′55.2″ : 88°34′48.9″), Ghoshpara (23°01′45.7″ : 88°34′50.0″) and Dharmatala (23°01′13.4″ : 88°34′59.0″) localities in 2006 (Figure 3). These were periodically monitored and found to yield arsenic-free potable water for about a year. The villagers have already started drinking this potable water and have benefitted by this measure. The sediment arsenic is, however, in a higher range but the water chemistry indicates very low arsenic, much below the permissible limit (Table 1) compared to the groundwater arsenic in the grey sand aquifers. It is obvious that the arsenic releasing process has still not begun in this aquifer. It is also postulated that the arsenic releasing process is not likely to operate in future, as this unit is protected from developing the reducing condition; the latter is reported to be responsible for releasing arsenic in the grey sand[14,20,21]. Moreover, this unit has already been transected so many times by the local driller to reach the underlying grey sand aquifer. So its intermixing by the upper and lower high arsenic water still remains insignificant. It is apparent that the overlying brown to bluish-grey hard clay is acting as a protective shield, thus making this orange sand arsenic-free.

The discovery of orange sand within the younger fluvial deposit of the Bengal delta and its monitoring to obtain arsenic-free groundwater from this unit, thus have a strong implication in protecting people from arsenic exposure. This finding also guides the development of future tubewells in this particular horizon, so that people from other areas in the Bengal delta would also get arsenic-free potable water. The tubewells being made at intermediate depths are highly economical and the water having low arsenic and iron would not require any surface filtration.

However, this orange sand unit has often locally been obscured by the channel activity of the later fluvial system depositing the overlying grey fine sand. But the geomorphological signature of the abandoned channels with convexity towards the earlier fluvial deposit depicts the preserved extension of orange sand. The same signature has been adopted in the present case, i.e. the Ghentugachi and Gotra villages (Figure 3). Accordingly, it is suggested that this signature may be used as a guideline for future tubewells. Consequently, the geogenic arsenic pollution in the Bengal delta can be eradicated by the foolproof geological solution provided in the present study.

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