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***Status Report***

# Contemporary Groundwater Pollution Studies in India

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This review contains a summary of the work done on arsenic and flouride pollution of the surface and groundwater in parts of the Indian peninsula and Ganga-Brahmaputra Alluvial and Delta Plains. Results of the investigation have been be categorized institutions wise with identification of the principal worker in the research group.

**Key Words: Water Pollution; Arsenic; Flouride; Alluvial and Delta Plains**

## Introduction

Extensive survey round the world has shown that groundwater polluted by arsenic (As) used for drinking purpose has highly adverse effect on human health. The effect become visible in less developed parts of SE Asia, where a large population depends on unfiltered and untreated groundwater from fluvial/deltaic aquifers. The lateral distribution of the arsenic pollutants in such aquifers is rather heterogeneous, although no definite clues are available to explain this heterogeneity in distribution. The location and severity of the arsenic pollution is therefore difficult to predict. Several scientific institutions and exploration agencies in the country and research groups in other countries have tried to pool in their expertise to unravel this hydrological mystery. From basic data generation to quantification and intelligent interpretation of observations and data sets have added to our knowledge about the mechanism of arsenic mobility through aquifers. In addition to the arsenic menace, fluoride pollution of the surface and ground water in many parts of the country have added woes to the poor populations of villages, totally dependent on untreated water from the wells and hand pumps.

In this review, we have summarized some of the publications on water pollution by the Indian researchers between 2008 and 2012. If we have missed out some publications, it should be considered inadvertent.

## Studies at the Indian Institute of Technology, Guwahati, Assam

### *Arsenic Program in Assam*

The UNICEF and Public Health Engineering Department (PHED) of Assam collaborated with the research group of Chandan Mahanta at the Indian Institute of Technology, Guwahati in a surveillance program for arsenic contaminated aquifers. Five zonal laboratories lead by a State Referral Laboratory (SRL) of the PHED were established to provide major support for this program. These studies indicated the presence of excess arsenic in groundwaters of the Brahmaputra Floodplain. A total of 5,729 samples in 192 blocks spread across 23 districts were tested and the rapid assessment results indicated water samples in 76 blocks out of a total 192 blocks had arsenic in excess of BIS guideline of 50 µg/l.

Subsequently, arsenic screenings were conducted with the help of three tier analyses using Arsenator field tests kit, UV-Spectrophotometery and Atomic Absorption Spectrophotometery with the following objectives:

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- To create a database for Assam on arsenic contamination of groundwater
- To identify safe-water sources with less than 50 µg/l of arsenic and painting those wells as Blue
- To identify all unsafe water sources with more than 50 µg/l of arsenic and painting those wells as Red
- Develop block level GIS maps

Based on the three tier analytical procedure, a total of 56,180 samples spread across 23 divisions in the Brahmaputra Floodplain in Assam were analyzed, out of which nearly 8% sources were found to contain arsenic concentration above 50 µg/l and nearly 30% sources had arsenic concentrations above the WHO limit 10 µg/l.

***Arsenic Mitigation Initiatives in Assam***

With the discovery of arsenic contamination of groundwater in this region, and consequent health implications, several initiatives were undertaken which included supply of oxygenated surface river water through piped networks to the arsenic contaminated areas. Brahmaputra Floodplain has enormous availability of surface water, hence such an initiative for arsenic mitigation is a viable option. The Greater Titabor Piped Water Supply Scheme is one such initiative where surface water from two major rivers-Dhansiri and Doiang Rivers is supplying arsenic free safe water to nearly 2 lakh population of Titabor in the Jorhat District in Assam.

Groundwater in this region is known for high iron content and therefore most people use conventional domestic filters for iron removal. It is well known that arsenic coexists with dissolved iron. Simple iron-based filters provide readymade protection from aseniferous waters. Exposed to air, iron gets oxidized and precipitate as iron hydroxide, carrying with it the coexisting arsenic and thereby get removed along with the iron. Ring Well Scheme, multi-village water supply scheme, rainwater harvesting and water recharging are some of the other options being adopted by PHED for arsenic mitigation in Assam.

***Fluoride contamination in groundwater of Assam***

High fluoride content beyond 1.0mg/l in groundwater has been reported from several isolated pockets in Assam and studied by IIT, Guwahati funded by the Department of Science and Technology, Govt. of India. The project aims at determination of the source of fluoride in groundwater and estimate the contamination level in different parts of the Guwahati city. A total of 164 groundwater samples of Guwahati city were analyzed and the results show fluoride in the range 0 to 4 mg/l. Southeastern part of the city showed the highest concentrations of fluoride ( 4 mg/l). Fluoride excesses are attributed to the leaching of fluorine bearing minerals from the regional rock type of granites and gneisses.

**Studies at the Lucknow University, Lucknow, U.P.**

***Arsenic in the Western Ganga Alluvial Plains***

Munendra Singh and his co-workers in Lucknow University are of the view that geogenic distribution of arsenic in sediments of the Ganga Alluvial Plains (GAP) is more or less same as in the sediments of the Ganga Delta Plains where severity of arsenic enrichment in groundwater is excessive and the health hazards are more readily visible. These workers infer that arsenic is released from the biotite containing sediments by natural weathering processes and then enters the hydrological system.

Forty-eight sediment samples from the Ganga Alluvial Plain (GAP) and its weathering products from the Gomati River around Lucknow were analyzed for arsenic by Instrumental Neutron Activation, in order to understand its source and nature of mobilization through the aquifers. Average concentrations of arsenic in the GAP sediments is 10.44 mg $kg^{-1}$, the Gomati River bed sediments contain 1.36 mg $kg^{-1}$ of arsenic and the Gomati River suspended sediments contain 5.3 mg $kg^{-1}$ of arsenic. Significant decrease of arsenic content from the alluvial sediments to the river sediments is a clear indication of its mobilization by chemical weathering processes of mineral biotite. In the GAP sediments, arsenic concentration varies from 3.0 to19.6 mg $kg^{-1}$ with average value of 10.4 mg $kg^{-1}$. Arsenic concentration varies in the Gomati River bed and suspended sediments from 0.12 to 4.36 mg $kg^{-1}$ and 0.66 to 14.91 mg $kg^{-1}$, respectively. In the GAP and the Gomati River sediments, arsenic concentration variability may be due to their mineralogical and sedimentological inconsistency. Arsenic concentrations in the GAP sediments fall within the range of arsenic concentration in the core collected from the Ganga Delta sediments. Average arsenic concentration of the Gomati River bed sediments (4.2 mg $kg^{-1}$) is lower than the Gomati River suspended sediments (14.9 mg $kg^{-1}$). It is due to higher content of quartz and lower content of clay minerals in the bed sediments than the suspended sediments. Compared to the GAP sediments, arsenic content in the bed and suspended sediments of the Gomati River is markedly decreased by weathering processes of the GAP. This depletion of arsenic content may have been caused due to high mobility of arsenic during the GAP weathering as a result of which the Gomati River has high dissolved load. During the monsoon season, rainwater reacts with sub-surface sediments of the GAP. Arsenic ions originate by incongruent dissolution of biotite and other ferro-magnesium minerals and are preferentially moved by solution to the Gomati River water.

***Fluoride in parts of the Western Ganga Alluvial Plains***

The Unnao district of Uttar Pradesh is known to have a number of habitable clusters which are affected by fluorosis due to drinking of fluorinated water. This disease was not known in this region a few decades ago and has been noticed only when it acquired serious dimensions. S. Kumar and his co-workers from Lucknow University discovered that villagers in this region were using ground water for drinking and cooking which has high fluoride content, much above the safe value recommended by the W.H.O. The Unnao district constitutes a part of the Western Gangetic Alluvium which is made up of Quaternary and Recent deposits. The source of fluoride in the ground water is geogenic and is being released in the water from the mica minerals in the sediments. In order to quantify the severity of fluorosis in the region context seven villages, four in the Asoha Block and three in the Nawabganj Block of Unnao district were selected for a detailed survey and 1550 persons were interviewed. The study included determination of fluoride content in the drinking water, economic condition of the family and the type of fluorosis. The population consists of low, average and high income groups while the low income group was more affected by fluorosis.

Three types of fluorosis were identified: dental fluorosis, muscular fluorosis and skeletal fluorosis. The most common is dental fluorosis which has largely affected the children. The analysis of canal, dug wells and hand pump water indicated 0-16 ppm F in the water.

**Studies at the Physical Research Laboratory, Ahmedabad, Gujarat**

A.K. Singhvi in collaboration with B.Weinman and his research group in the University of Columbia have tried to link aquifer-depositional-ages to shallow groundwater arsenic heterogeneity in several study sites in Asia. The sedimentological-geochronological work using optically stimulated luminescence shows that groundwater arsenic heterogeneity can be explained by an aquifer's depositional history. In Bangladesh, variable thicknesses of the floodplain's mud-capping (0-13m) allows for differential flushing in the shallow aquifer. In turn, this allows for differential groundwater arsenic concentrations over 10's of meter distances, supporting a physical (flushing) control on arsenic by the sediments. In Vietnam's Van Phuc Red Riverbend, there is a more "chemical"- type of sedimentary control, with higher groundwater arsenic sourced in Holocene sands, while lower arsenic is seen in water from the Pleistocene units. The same trend was also observed in Parasi, Nepal and in other independent studies and is different than the more "physical" sedimentary control observed in Bangladesh, indicating more of a reactive-transport or chemical (weathering) control by the sediments. Despite these differing chemical (Van Phuc in Vietnam and Parasi in Nepal) and physical (Araihazar in Bnagladesh)) effects on groundwater arsenic by their host sediments, one commonality between these and other arsenic-prone regions is that abandoned-channel facies consistently serve as local depocenters for muds and/or Holocene sand units, both of which correlate to higher groundwater arsenic.

**Studies at the University of Kalyani, Kalyani, W.B.**

***Arsenic in the Ganga-Brahmaputra Deltaic Plains of West Bengal***

Debashish Chatterjee's research group working from the Department of Chemistry at Kalyani University, West Bengal, have published a fairly large number of research articles concerning contamination of groundwater with arsenic in different parts of West Bengal. These studies involved geochemistry of groundwater to interpret the geological controls of the contaminants. These workers also studied migration of arsenic contaminated groundwater and suggested methods for short and long term remediation. Isotopic studies have been done to understand geochemical process in arsenic generation, understand the sources and infer flow and mixing of groundwater in Bengal delta plains. Recent studies by this group includes risk based modeling to assess arsenic exposure *vis-a-vis* rice grain size with the help of PDTI route. This group identified and postulated multi-depth and multi-mechanism of arsenic mobilization in various parts of the contaminated areas of the Bengal Delta Plain. Laboratory and field scale studies were also conducted on bio-availability of arsenic in contaminated soil. Proxy materials have been used on field scale to estimate the role and characteristics of microbes in low versus high arsenic areas. These workers made typological groundwater comparisons between delta front and delta plain to suggest role of sea-level changes for arsenic sourcing in the Bengal Basin along with anthropogenic factors. These workers are of the view that no unique mechanism can be universally applied to address the heterogeneous distribution of arsenic.

**Studies at the Jadavpur University, West Bengal**

***Arsenic Pollution in the Ganga Delta Plains***

Arsenic pollution of groundwater in parts of the Ganga-Brahmaputra Delta in West Bengal and Bangladesh, in parts of narrow entrenched lower-middle sections of the Gangetic plains in Bihar, eastern U.P. have been studied by S.K.Acharyya and B.Shah. They have also studied arsenic contamination in hard-rock areas such as Ambagarh Chowki Block in Chhattisgarh which is confined to a rift belt exposing meta-acidic volcanic rocks and coeval granites where weathered rocks and soils are enriched in arsenic and are released to groundwater.

Acharyya's group suggested that arsenic bearing minerals are absent or very rare in the contaminated alluvial aquifers of Ganga delta and flood plains. Instead, like other previous arsenic researchers, they also subscribe to the theory that arsenic occurs adsorbed on hydrated iron oxide that coat sediment grains and organic matter, which are preferentially entrapped on organic rich deltaic and less frequently floodplain sediments of Holocene age. These workers suggested that alluvial cover on the Pleistocene terraces in the Bengal Basin and the inter-fluve uplands in Ganga plain are oxidised and therefore largely free of arsenic contaminants. Aquifers in the Pleistocene terraces in the Ganga delta and interfluve uplands in the Ganga Plain possibly flushed out the released arsenic, if any, because of higher hydraulic gradient and longer duration of groundwater flow. Thus, arsenic contamination is considered restricted to Holocene palaeo-channels and deltaic lowlands. In other words, arsenic contamination in Bengal Delta Plains is stratigraphically controlled and within the Late Pleistocene-Holocene (~28,000 to 6000 yr. B.P) sediments.

Acharyya and his group subscribe to the hypothesis that the arsenic is mobilized to groundwater by bio-mediated reductive dissolution of hydrated iron oxide as arsenic is known to have great affinity for iron. Ferrous iron is soluble and thus releases arsenic, whereas, arsenic remains immobilized in ferric hydroxide under oxidizing environment. The reduction process is possibly mediated by iron-reducing bacteria. Strong reducing nature of groundwater in the Bengal Basin and parts of affected flood plains is indicated by high maximum concentration of iron ($\leq$ 9-36 mg/l). These workers believe that arsenic is not exclusively derived from the Himalaya and the rivers from the peninsular shield including Damodar basin also contributed to the arsenic budget of the groundwater in the Bengal Delta Plains.

Long standing suggestion of utility of dug-wells as sources of arsenic free water has been again emphasized by these workers.

## Studies by the Central Ground Water Board

### *Arsenic Pollution in the Middle Ganga Plains*

The researchers (D. Saha) of Central Ground Water Board (CGWB), Govt. of India contributed to the study of groundwater contamination in the Middle Ganga Plains (MGP) of Bihar. In contrast to the degradation regime in western parts of the Ganga Plain in Uttar Pradesh, this part of the plain is undergoing aggradations and filling. Alluvial thickness in this sector varies from tens of meters to few hundreds of meters. Sand thickness is considerable and makes potential aquifers down to the explored depth of 350 m below ground. In several isolated sectors, mostly along the Ganga, the groundwater in the upper parts of the shallow aquifer (~50 m depth), has arsenic load beyond the regulatory limit of 50 ppb. Since its detection in 2002 in Bhojpur district, the CGWB have explored various issues like spatial distribution of arsenic, style of mobilization, identification of arsenic-safe aquifers, behaviour of contaminated and non-contaminated aquifers and evolution of the alluvial geomorphology in the affected area.

The works has remained focused in the Sone-Ganga interfluves of MGP. Though, the axial drainage of Ganga bears a trend of southward migration due to rise in the Siwaliks, local structural perturbations and high sediment budget at few places from south have made the river oscillatory. Except few patches, nearly the entire stretch of Ganga in MGP is associated with flood plains on both the banks. In the Sone-Ganga interfluves, such flood plain is the widest (5-20 km) in entire MGP. This plain is dotted with number of meander scars of Ganga and associated cross bar channels of smaller dimension.

Patches of palaeo-abandoned channels of Ganga show high groundwater-arsenic within the shallow depth. The clay plugs in the abandoned channels are 12-15 m thick and possess high argillaceous matter of black colour composed up of organic carbon. The organic carbon accompanying groundwater, when comes in contact with hydrated iron oxide present as coatings on sediment grains, promote reductive dissolution releasing arsenic in groundwater. The spread of the reducing environment depends upon the hydraulic gradient, groundwater flow direction and volume of fresh oxic water recharge that reaches the spreading anoxic front. The more sandy areas along the scroll bar ridges and levees yield low concentration of arsenic as the oxic groundwater in such areas favour stability of hydrated iron oxide.

The observations have indicated that Sone River has remained avulsive (once in ~1000 years) and through this process, it has formed a megafan. The Ganga has entrenched upon its surface and the contamination lies in the Himalayan derived finer (grayish to black colour) Ganga sediment of Holocene age. A two-tier aquifer system has been delineated in the affected area within a depth of 250 m below ground. The upper aquifer extends down to the depth of 90-110 m and below it there is middle clay of ~25 m thickness, separating the deeper aquifer. The groundwater flow is sluggish in the upper aquifer in contrast to the deeper aquifer, which constitute the Older Alluvium. Water level remains largely within 2-8 m below ground and the piezometric level of the deeper aquifer invariably remains above the phreatic surface under normal condition. Transmissivity of the arsenic-safe deeper aquifer is 3000-7000 $m^2$/day and storage coefficient is 0.001-0.004. The $\delta^{18}O$ signature and the $C^{14}$ values of the deeper aquifer reveal its flow regime to be separate from the shallow contaminated aquifer. The age of the deeper groundwater has been found as 3000 years in contrast to ~50 years from shallow aquifer.

The hydraulic set-up and resource availability of the two aquifer systems, suggest that the deeper aquifer can be exploited for community water supply and irrigation. The deeper aquifer does not receive any recharge from the overlying contaminated aquifer, rather getting its recharge from further south in the Pleistocene deposits.

## Studies at Indian Institute of Technology, Kharagur, Kharagur, West Bengal

### *Studies of Deeper Groundwater Arsenic in West Bengal*

The deeper groundwater of the Bengal Delta Plains has long been considered as an alternate, safe drinking water source in areas in contrast to arsenic contamination in near-surface groundwater. A recent study by A. Mukherjee from IIT, Kharagpur and his research group documented a wide-spread elevated arsenic concentration in deeper groundwater (up to 60%) in parts of the western Bengal basin. Deeper groundwater is defined here as non-brackish, potable ($Cl^- = 250$ mg/l) groundwater available at the maximum accessed depth (~80 to 300 m). The extent of elevated arsenic in deeper groundwater in the study area seems to be largely controlled by the aquifer-aquitard framework. Arsenic-contaminated deeper groundwater is mostly encountered north of 22.75 °N latitude (up to 80%), where an unconfined to semi-confined aquifer consisting of Holocene- to early Neogene gray sand dominates the hydrostratigraphy to 300 m depth below land surface. This research group delineated the hydrostratigraphy of the study area by construction of a three-dimensional, finite-difference grid, block-centric lithologic model. The model provided a regional-scale interpretation of the complex aquifer-aquitard framework existing in the western part of the Bengal basin. The resolution of the model was 1000 m (x) x 1000 m (y) x 2 m (z) from surface to a depth of 300 m below mean sea level (bMSL). The model interpretation of the hydrostratigraphy indicates the presence of a single, semi-confined aquifer (main aquifer), thickening from ~80 m bls in the north of the modeled study area to ~300 m bls toward south (Bay of Bengal) and east (Bengal foredeep basin), and overlying a basinal-scale basal clay aquitard. The southernmost areas exhibit a multilayer system where the aquifers are separated from each other by thick aquitards. A few confined, isolated aquifers are present within the basal aquitard. However, isotopic ($\delta^{18}O$ and $^{2}H$) and chemical signatures of the groundwater residing above and below these aquitards and in other parts of the main aquifer are statistically similar. Some of these workers also described the 3-D, seasonal regional groundwater flow through heterogeneous, anisotropic aquifers of the study area by simulating the pre-pumping era (pre-1970s), present-day (pumping as of 2001), and future (pumping projected for 2011 and 2021) scenarios through the inferred hydrostratigraphy. Groundwater modeling in the study area suggested that prior to the onset of extensive pumping in the 1970s (pre-development), topographically-driven, regional-scale flow occurred within the major aquifer system during the dry season. The southward flow, calculated from pre-development models of (2007, indicated a probable horizontal and vertical hydraulic gradient of 0.09 m/km and 0.06-0.08 m/m, respectively. With the initiation of pumping, several local- to intermediate-scale flow systems replaced the dominant regional flow system. The hydraulic gradients were dictated by the pumping centers and aquifer architecture. Cones of depression with local-scale, vertical convective flow cells were formed corresponding to these centers of depressions. In areas of acute pumping, water levels were found to have declined significantly, as indicated by dry cells. Mukherjee and his co-workers collected groundwater samples from deep public water supply wells along the simulated, pre-1970s, regional groundwater flow path, which were analyzed for major and minor solutes, dissolved gases and stable isotopes. Geochemical modeling and quantitative analyses indicated that carbonate dissolution, silicate weathering, and cation exchange are the main processes of chemical evolution of major solutes of the deep groundwater. The main aquifer water also evolved by mixing with seawater from the Bay of Bengal and connate water. The redox and minor solute chemistry indicated a predominantly anoxic aquifer, with an increasingly reducing hydrochemical environment with depth, and a complex redox equilibrium scenario, at least in parts of the study area where metal (Fe-As) reduction predominates. Enrichment of dissolved inorganic carbon in $^{13}C$ with depth suggests that some $CH_4$ has been derived from $CO_2$ reduction rather than originating from peat, a suggested redox driver for As mobilization in the Bengal basin. Outliers in depth trends of $SO_4^{2-}$ and As(III)%, and other bivariate plots, suggested localized cycles of reduction and re-oxidation. This geochemical signature was further verified by a localized study in Bhagirathi sub-basin (part of western Bengal basin) and its comparison with Meghna sub-basin in Bangladesh. It was found that the biogeochemical triggers of arsenic mobilization are influenced by complex redox disequilibria, caused by overlapping redox zones. Results of numerical modeling and profiles of environmental tracers at a local-scale study site within the sub-basin suggest that deeper groundwater abstraction can draw As-contaminated water to 150 m depth within a few decades, which might be related to the advent of wide-scale irrigational pumping in West Bengal and rest of India.

**Studies at the School of Environmental Studies, Jawaharlal Nehru University, New Delhi**

***Arsenic Pollution Around Varanasi in Ganga Plains***

N J Raju studied ground water in and around Varanasi city and found the there is virtually no arsenic (<10 µg/l) in the groundwater inside the city due to its location over the Pleistocene older alluvium and its position in upland surfaces (western side of Ganga). However, arsenic menace was found in the peripheral areas. Analysis indicated slightly alkaline water with low concentration of $HCO_3$ at 10 to 20 m depth. This is the most important anion species, which competes with As for adsorption sites at mineral surface (e.g. Fe/Mn oxyhydroxides, clay minerals and weathered mica) and contributes arsenic to the groundwater. Villages located in Holocene newer alluvium sediments (eastern side of Ganga) in entrenched channels and floodplains of Ganga River have arsenic contaminated groundwater. Arsenic-enrichment in groundwater of the study area shows a close relationship with major geomorphological units. The elevated arsenic enrichment in the eastern part of the Varanasi area (Middle Ganga Plain) is due to discrete phases of arsenic sorbed Fe-oxyhydroxide coated sediment grains preferentially entrapped in Holocene newer alluvial organic rich argillaceous sediments in entrenched channels and flood plains. The other geochemical processes active in the As-prone shallow aquifers of Newer Alluvial belt are seepages from domestic sewage and dissolution of silicate minerals Dug wells are found to be arsenic safe because of their oxygenated nature. Villages such as Bahadurpur, Ratanpur, Madhiya, Semra, Bhojpur, Jalilpur, Kateswar, Bhakhara and Kodupur with wells in the depth range of 40-70 m are affected by arsenic. With increase in hand pumps in the area and gradual decrease in open dug wells(which are easily polluted by surface discharges) arsenic menace has considerably increased. Analysis of groundwater indicated that arsenic content varies from below <3 µg/) to 80 µg/l while the upper permissible limit of arsenic in potable water is 50 µg/l in India and the W.H.O. limit is 10 µg/l. The arsenic content in groundwater samples indicates that 14% of the samples exceed 10 µg/l and 5% of the groundwater samples exceed 50 µg/l. The high As concentration is found in some of the villages situated in the Holocene Newer Alluvium (eastern side of Ganga River) of the Varanasi environs. Preliminary survey could identify most of the arsenic contaminated hand tube-wells in the villages of Bahadurpur, Madhiya, Bhojpur with arsenic more than 50 µg/l. Some of the villages such as Ratanpur, Semra, Jalilpur, Kateswar, Bhakhara and Kodupur have arsenic content more than 10 µg/l and are located in entrenched channels and floodplains of Holocene Newer Alluvial sediments which are situated close to the concave part of the meandering Ganga River in Varanasi environs. However, dug wells and hand tube wells on the western side of river Ganga, have arsenic safe groundwater due to their position on Pleistocene older alluvium sediments though arsenic and iron content in sediment samples are found in high concentrations in the shallow to medium depths. This may be due to lack of organic matter for the reduction of iron oxides which helps in releasing arsenic to groundwater in the western part of the study area. The relatively low values of dissolved iron (<0.7 mg/l) in the Middle Ganga Plains (i.e. Uttar Pradesh and Bihar) compared to higher values in the West Bengal (up to 36 mg/l) and Bangladesh (up to 30 mg/l) indicate that the Middle Ganga Plain environment may not be sufficiently reducing to mobilize iron and arsenic in groundwater. In general, the groundwater occurring in the hand tube wells are contaminated with arsenic when compared to dug wells in the study area.

**Studies at the University of Delhi, Delhi**

***Arsenic in the Chattisgarh Region in Madhya Pradesh***

Groundwater samples from the Kaudikasa village in Rajnandgaon district of Chattisgarh, were analyzed by Wagtech Digital Arsenator by D. Shukla and C.S. Dubey's research group. The analysis shows high concentration of arsenic with maximum exceeding 250 lg/l. Petrographic studies of the country rock granite display the presence of altered realgar/pararealgar, orpiment, and tennantite. The complex geology of area is represented by extensive shearing as shown in the remotely sensed maps. PCA images of lineaments along fault planes show sinistral shearing. This is confirmed by the change in the course of the river drainage. The uranium exploratory mine at Bodal, situated on the SE side of the study area, with NW-SE and N-S mineralized lineaments and granites and pegmatites at the intersection of these lineaments, seem to provide arsenic for the groundwater pollution. Away from these lineaments, the arsenic values show decrease in the shallow reaches of the aquifer and depth distribution pattern is similar to that of the Bengal Delta Plains. Similar situation is seen in the Durgo Kondal area of Kanker district.

***Arsenic in the National Capital Region***

Study of 120 surface and groundwater samples from the Yamuna Flood Plains in the capital city encompassing Geeta Colony, Mayur Vihar, Wazirabad, Nigambodh Ghat, Kotla Mubarakpur and Rajghat, Indraprastha and Badarpur coal-based thermal power plants revealed high arsenic concentrations beyond the W.H.O. standard with maximum recorded up to 180 ppb. Nearly 55% of these samples have arsenic content more than W.H.O. limit of 10 ppb. The coal and fly ash generated from the Rajghat coal-based thermal power plant analyze 200 and 3,200 ppb of arsenic. Coal samples used in these power plants contain arsenopyrite. Maximum concentration of arsenic contamination is found within a 5-km radius from power plant, hence arsenic in the waters of Delhi is primarily anthropogenic and is linked to coal-based thermal power plants. An estimate shows 5.5 Tonnes/year of arsenic is being discharged into the Yamuna River from the Rajghat power plant. It is therefore inferred that coal-based power plants in West Bengal and Bangladesh, may have added more arsenic to the already arsenic contaminated groundwater of the region.

***Arsenic in the Bengal Delta Plains: Barasat, 24-Parganas of West Bengal***

Investigations on arsenic pollution of the groundwater in the Bengal Delta Plains was initiated by the research group of D.M. Banerjee with British Council-UGC linked collaboration with the London Arsenic Group headed by J.M. McArthur of the University College London and Peter Ravenscroft. The collaboration was extended to many institutions in Britain, Central Ground Water Board, New Delhi and Kolkata, and Stable isotope lab in the Indian Institute of Technology, Kharagpur. The study area comprise three main villages, Joypore, Ardivok and Moyna (referred as JAM) in Barasat District near Kolkata. These studies are based on observations in the selected villages with confirmation of results by observations in several other villages in the neighborhood.

The literature from all over the world indicate that there was world-wide decline in sea-level between 125 ka and 18 ka which exposed deltaic sediments to weathering and erosion. In the study area of JAM, this phase of weathering resulted in the formation of an impermeable clay palaeosol which now lies at about 25 m. depth. It has been designated as the Last Glacial Maximum Palaeosol (LGMP) which this group believe, exerts a strong control on groundwater flow in the delta plain, and so on the severity of arsenic pollution in the shallow aquifers (< 50 m depth) of the region. This pattern of pollution seems applicable to the entire Bengal Basin.

The distribution of arsenic in the region is quite heterogeneous, the reason for this is still unresolved. In trying to explain this heterogeneity , members of this group mapped arsenic pollution in groundwater using 659 wells across 102 $km^2$ of West Bengal, and logged 43 boreholes, to reveal that the distribution of As-pollution is governed by subsurface sedimentology. Across 47 $km^2$ of contiguous palaeo-interfluve, the shallow aquifer (<70 mbgl) was found to be unpolluted (<10 μg/L), the reason being capping by the red-clay rich palaeosol (the last glacial maximum palaeosol, or LGMP ) at depths between 16 and 24 mbgl. It is inferred that the LGMP protects the aquifer from vertical recharge that might carry arsenic rich water or dissolved organic matter that might drive reduction of sedimentary iron oxides and so release arsenic to groundwater. In 55 $km^2$ of adjacent palaeo-channels, the palaeosol is absent, so arsenic is able to invade the aquifer and dissolved organic matter can occur. For this reason, ground water tapped from the palaeo-channel is invariably polluted by arsenic (>50 μg/L). All these years the role of palaeosols and, in particular, the LGMP, has been overlooked as a control on groundwater flow and pollutant movement in deltaic and coastal aquifers worldwide. Investigations on filtration of pollutant in such environments must take into account the presence of and the location of LGMP (or other palaeosols) to understand the recharge in the basin. The recharge moves downward in palaeo-channel regions that are separated by palaeo-interfluvial regions where vertical recharge to underlying aquifers cannot occur and where horizontal flow occurs above the LGMP and any aquifer it caps.

This study group found unpolluted aquifers of Pleistocene brown sand, at depths between 25 and 60 m, which underlie palaeo-interfluves and are capped by the LGMP at a depth of 23-25 m. The interpretation is that the palaeosol prevents downward movement of water and so protects the underlying brown sands of the shallow aquifer from reduction by organic carbon derived from overlying organic-rich mud and silt. In palaeo-channels, where the LGMP is absent, the Pleistocene sands of the shallow aquifer, at depths of 30 to 45m, have been reduced, are grey in colour, and are severely polluted by arsenic because of the absence of LGMP and allows arsenic and dissolved organic matter from overlying sediments to spread pollution downward. Horizontal piezometric gradient of ~0.0009 show that groundwater in the study area is moving northward at a rate of 30 metres per year from the As-polluted palaeo-channel region of the shallow aquifer towards the unpolluted, palaeo-interfluvial region. The brown sands in the palaeo-interfluves retard the movement of arsenic by sorption and contain reserves of unpolluted water that could last many tens of years at current rates of arsenic migration of 1-5 m meters per year.

The studies indicated arsenic concentrations in the wells to vary from nil to >1000 μg/l. As mentioned above, the unpolluted aquifer underlies the palaeo-interfluves, and the polluted parts is found in the palaeo-channels; the sequences are distinguishable in the field by their sharply contrasting apparent resistivity. No relation was found between the severity of arsenic pollution and either tritium concentration or water age, which ranges from < 2 y to >50y. Ages exceed 50y where return irrigation water from deep wells (> 175m) supplies tritium-dead water for recharge.

To reiterate the scenario prevailing in the Bengal Delta Plains, it may be noted that wherever the palaeo-interfluve sequence is capped by a Pleistocene palaeosol of impermeable Brown Clay, the Shallow Aquifer of brown Pleistocene Sand contain ground water with <10 µg/l of arsenic., because the palaeosol protects the aquifer from reduction by organic matter in the overlying 22 m of organic-rich, peaty Holocene aquitard. By contrast, along the course of Pleistocene paleostreams, where the palaeosol is absent, palaeochannels cut into the brown Pleistocene Sand and are filled by grey Holocene Sand beneath a thinner overlying aquitard that contains less organic matter. This Holocene Sand contains groundwater and is severely polluted by arsenic.

The Holocene channel-sands are in hydraulic continuity with both underlying and laterally-adjacent Pleistocene sands, thus allowing water polluted with arsenic to invade the latter. Invasion is accompanied by reduction, driven by dissolved organic matter from the overlying aquitard and in the aquifer itself. Topography, and pumping for irrigation, drive ground water flow in the Shallow Aquifer to the NNE from polluted regions to unpolluted regions at a maximum horizontal velocity of 30 m per year.

***Study of Ponds in Arsenic Pollutted Region***

Avindya Sarkar and S.Sengupta, the investigators from the Stable isotope lab of IIT, Kharagpur working with DU-London Research group studied time-series data collected over two years for $\delta^{18}O$, $\delta^2H$, and Ca, Mg, K, and Cl, concentrations for 10 ponds in, and up flow of, an arsenic polluted region in and around JAM. The study involved comparison of composition of arsenic-polluted ground water from wells with the composition of waters in ponds up flow, and within the range of influence, of the wells. Conservative tracers ($\delta^{18}O$, $\delta^2H$, K), and other tracers (Ca, Mg) that are considered conservative in the waters, show that pond water and groundwater are distinct and do not overlap in composition. These data show that water from ponds cannot be identified in arsenic polluted groundwater, so putative DOC in pond water cannot mix into the arsenic polluted groundwater that was sampled. Separate estimates of the degree of recharge from ponds to groundwater, using calculations based on temporal variations in salt content and isotopic composition in ponds, and salt balance, show that insignificant amounts of arsenic polluted groundwater are derived via pond recharge. It follows that pond water in the study area does not contribute significant mass to arsenic-polluted groundwater and so does not provide organic matter to aquifers in amounts sufficient to drive reduction.

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