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**Geologic origin of arsenic groundwater contamination in Maner block, Bihar,
India**



Title : Geologic origin of arsenic groundwater contamination in Maner block, Bihar, India

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*To my family and friends,
who have always been near me
despite the distance
during the best and the worst.*

«Και μόνο το γεγονός ότι αναρωτιόμαστε ποιά είναι η πιθανή επίλογή, φθείρει και θολώνει αυτό που θα μπορούσαμε να επιλέξουμε.»

Preface

This report describes the process and result of a research and fieldwork project in Maner block, Bihar, India. The project concerns geological research in the state of Bihar, India with the purpose to determine the Quaternary stratigraphy of sedimentary depositions and provide with a sedimentary model of the area.

Data obtained and implemented during this research were used as part of the curriculum of MSc Engineering Geology to supply with data for the Final Thesis of Sotiria Lourma, in order to assess the release and mobilization mechanism of arsenic in groundwater and as a consequence in drinking water.

The research project was hosted by the Department of Environment and Water Science, Anugrah Narayan College, Patna for the period of 1st September 2010 to 15th November 2010, under the supervision of Dr. Ashok Ghosh and Dr. Nupur Bose. A.N.College provided with all the necessary guidance and support for the project, as well as with laboratory equipment and laboratory testing on samples.

Fieldwork, travel expenses within Bihar, equipment and a part of accommodation costs were funded by Molengraaf fonds. Part of travel expenses to and from India as well as personal expenses was funded by CiCAT and by Studiefondsen TU Delft.

This project owes its realization to the workers of the drilling staff, who literally sweated in order to complete all the tough work of drilling with accuracy and persistence.

I would like to warmly thank Prof. A. Ghosh and Dr. N. Bose (A.N. College, Patna), Prof. Dr. J. Bruining and Dr. M.E. Donselaar (TU Delft) for their scientific and personal support and PhD student Ajay Bhatt (TU Delft), whose presence during the project was crucial for its realization.

Special thanks to the BSc Students of A.N.College Anil, Anubhav and Satish for their devotion, patience and hard work.

Acknowledgments go to Rajeev Kumar and Dr. Seema Sharma for their contribution and concern for laboratory testing, to Dr. Radheshyam Rai (Departemento de Enganharia, Universitario de Santiago, Aveiro, Portugal) for accepting to carry laboratory testing on the obtained samples, to Jack Voncken (TU Delft) for his continuous effort and care for SEM testing and to Dr. Sahu (Central Ground Water Board, Patna), Dr. Dayal (former Director, Geological Survey of India) and Dr. Sinha (B.N.College, Patna) for providing me with their knowledge regarding the geology of the studied area.

Finally, I would like to add that this research project is a pioneering work, which aims to contribute towards a deeper understanding and possibly provide with a solution to the groundwater arsenic contamination problem that emerged in Bihar state during the last decade. I hope that a beneficial result for the local communities will be reached and that further research will take place within the Patna district to assess the issue in detail and suggest possible solutions.

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Summary

Arsenic contamination of the groundwater and as a consequence, of the drinking water, has developed to a major problem for many regions globally during the last decades (Chile, China, United States, Argentina, and Mexico). The issue of Arsenic contamination has already been studied extensively in West Bengal, India and Bangladesh, which are some of the affected areas. The importance of studying arsenic groundwater contamination lies in the fact that it has impacts on human health, which indicate that proper measures need to be taken towards a safe drinking water solution.

Despite the fact that many researchers around the world have tried to determine arsenic release and mobilization mechanisms, it appears that this is a procedure that is controlled by rather regional parameters and therefore, there is no standard mechanism that can be taken for granted. Each region has different geological and stratigraphic characteristics and since arsenic is naturally formed and released in groundwater for most of the contaminated cases, each region needs to be carefully studied separately.

The state of Bihar in India and more specifically the region close to the conjunction of the Ganga and Sone Rivers was chosen as a research location, because, contrary to other affected regions, no geologically related research regarding Arsenic has been carried out there until now.

The initial target of this research project was to build a 3D sedimentary architecture model of the area using PETREL software. This model could later be used in flow modeling. The study was then focused on determining the various depositional environments of fluvial sediments and in finally correlating them with the presence or absence of Arsenic in the groundwater. In addition, this study aims to provide a suggestion regarding the possible source of Arsenic in the groundwater for the region of Maner in Bihar.

There are two basic hypotheses that will be investigated during this research. One is that Arsenic is confined within the Newer Alluvium of the Ganga River (Holocene sediments) and especially within the point bar alluvial depositions. The second is that Arsenic is already present within the sediments and released in the groundwater due to the presence of Iron oxides in Iron rich minerals (biotite and micas in general) or Iron coatings on Quartz and clay grains.

The following methodologies were applied in order to achieve the research purpose. First, literature study of existing research in the area and other Arsenic affected regions was carried out. Then the study area was visited and fieldwork was carried out, which included drilling three approximately 50 m deep boreholes by hand sludging and logging the sediment cores that were obtained as accurately as possible. Hand sludging was used as the drilling technique, even if it is suboptimal for the initial research purpose, because of financial and time constraints. Therefore, it was not possible to obtain undisturbed soil samples while drilling. As a result, core logging, which is an important input for a 3D model, was not always successful.

Then, Ultra Violet Spectrophotometry testing was carried out in order to measure the Arsenic content in soil and Scanning Electron Microscopy and X-ray Diffraction in order to determine the mineralogy and chemical composition of the soil samples. In addition, existing measurements of Arsenic levels in drinking water were registered and the coordinates of the handpumps were recorded, using a Global Positioning System device (GARMIN).

The purpose of this research is to combine existing knowledge regarding the source of arsenic and specific sedimentary settings in order to correlate local geological characteristics with the presence or absence of arsenic in the groundwater and to suggest a possible source of arsenic for the region of Maner.

The results support the hypothesis that it is essential to consider the origin of the sediments to localize regions of high arsenic content.

Introduction

In Bihar, India, like in many areas downstream of the Himalayas, arsenic is contained in fluvial deposits, mainly of Holocene age. Arsenic occurs naturally in small quantities in almost any type of geological formation. Important sources of Arsenic within unconsolidated sediments are iron oxides that contain absorbed arsenic. These oxides can be encountered as coatings on quartz and clay grains, or can be released after chemical weathering of biotite. Biotite is a mica mineral with a general chemical formula $K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$, originally found in igneous and metamorphic rocks. Biotite may undergo weathering and release iron oxides when transported and re-deposited in sedimentary formations.

The arsenic affected sediments have mostly been transported by the Ganga River from the Himalayas and deposited in the Middle Ganga Plain. It has been shown by previous research that arsenic affected groundwater is confined to the aquifers of the Holocene sediments (Newer Alluvium), while aquifers in the Pleistocene sediments (Older Alluvium) are relatively arsenic free.

In addition, arsenic levels in the soil appear to be higher in sediments that have been deposited in the point bars and abandoned channels along the course of the Ganga River. The Ganga River shows a typical meandering pattern. This means that various sedimentary environments that earlier belonged to its active course were at some point abandoned. These abandoned features, like oxbow lakes and old point bars, develop swampy conditions and hence produce a reductive environment, which is conducive in releasing arsenic from the sediments to the groundwater.

Holocene sediments of Maner region, State of Bihar, India were studied in detail by drilling three boreholes of approximately 50 m depth. The stratigraphy was registered in borelogs and soil samples were taken for laboratory analysis. The samples were tested with Ultra Violet Spectrophotometry in order to measure arsenic concentration in the soil and Scanning Electron Microscopy and X-Ray Diffraction in order to determine their mineralogical and chemical composition.

Study area

Bihar is located in the north - eastern part of India (Latitude: 24° -20'-10" S to 27° -31'-15" and longitude 82° -19'-50" to 88° -17'-40" E). It is an entirely land-locked state that lies mid-way between the humid West Bengal in the east and the sub humid Uttar Pradesh in the west which provides it with a transitional position in respect of climate, economy and culture. It is bounded by Nepal in the north and by the state of Jharkhand in the south (Government of India).



Figure 1 Location of Bihar state in India. Image obtained by Google Maps. In the general map of India on the left, the location of Bihar is indicated with red color. The fieldwork location is indicated with red color on the map of Bihar.

The state of Bihar has a geographical area of 94,163 km². It is the third most populated state of India, with a population of over 83,000,000 of which about 83% lives in rural areas and 58% is below 25 years old. The capital city of Bihar is Patna.

Geographically, Bihar is divided into two unequal halves by the river Ganga, which flows through the middle from west to east: these geographical units are the Northern Ganga Plains, Central Ganga Plains and the southern Chotanagpur Plateau region. These geographic units occupy 30%, 24% and 46% of the area respectively. Normal average rainfall is of about 1203.5 mm, 70% of which comes from SW monsoon. The total annual replenishable groundwater resource in the state is 27.42 billion m³ with an average state of development of about 39% (Central Ground Water Board, 2010).

Bihar experiences three climatic periods: a hot season from March to May, a rainy season between June and September, and a cold season from November to February.

Regarding Maner block, as of 2001 India census, it has a population of 26,912. Males constitute 53% of the population and females 47%. Maner has an average literacy rate of 52%, lower than the national average of 59.5%: male literacy is 61%, and female literacy is 42%. In Maner, 19% of the population is under 6 years of age.

The economy is based on agriculture. Corn and rice are the mainly cultivated crops. Fishing is one of the extended activities as well. The block consists of a large number of densely placed villages. Each village has a Primary School, while the main village among them hosts the High School.

One of the most famous medieval sites in Bihar is located in Maner block. Maner Sharif is located 30 km West of Patna, and is one of the chief spiritual sites in India. It houses two Muslim Temples: Makhdoom Yahya Maneri, also known as the Bari Dargah, and Shah Daulat, popularly called Chhoti Dargah.

Fieldwork location

Fieldwork was carried out near Maner, Patna district (Fig. 2). Maner was chosen as a study area because during previous research regarding groundwater contamination from arsenic, it was indicated as one of the areas where arsenic hotspots were encountered (Central Ground Water Board, 2010; Ghosh, 2003).

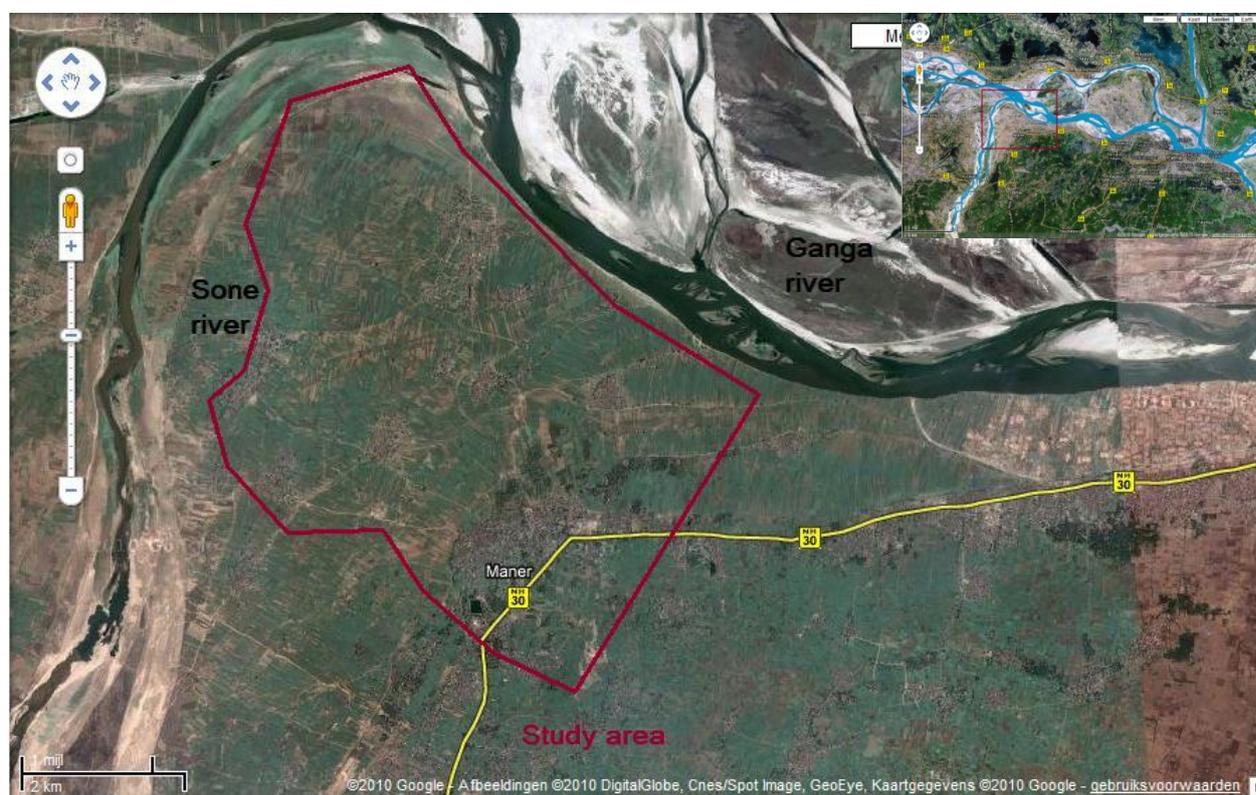


Figure 2 The research project location within Maner block, Patna district, Bihar. The area is located at the junction of Sone River with the Ganga River and comprises a cluster of villages and extended croplands. Image obtained by Google Maps.

Geology, geomorphology and hydrogeology of Bihar

This study is focused on sediments that belong to the sedimentary infill of the Ganga Foreland Basin, part of the Himalayan Foreland Basin. It is therefore of great importance that the general geological setting of Northern India and especially of Bihar are properly studied and understood. The following paragraphs present the geological framework, based on existing literature. The geological setting of Maner block and the study area, as it was studied while on fieldwork will be analyzed in detail in the chapter of Data implementation.

Geological framework of the study area

Tectonic evolution of the Himalayan Foreland Basin

The Sub-Himalaya is popularly referred to as the Himalayan Foreland Basin, which is one of the largest and most dynamic terrestrial basins in the world (Kumar, Ghosh, Mazari, & Sangode, 2003).

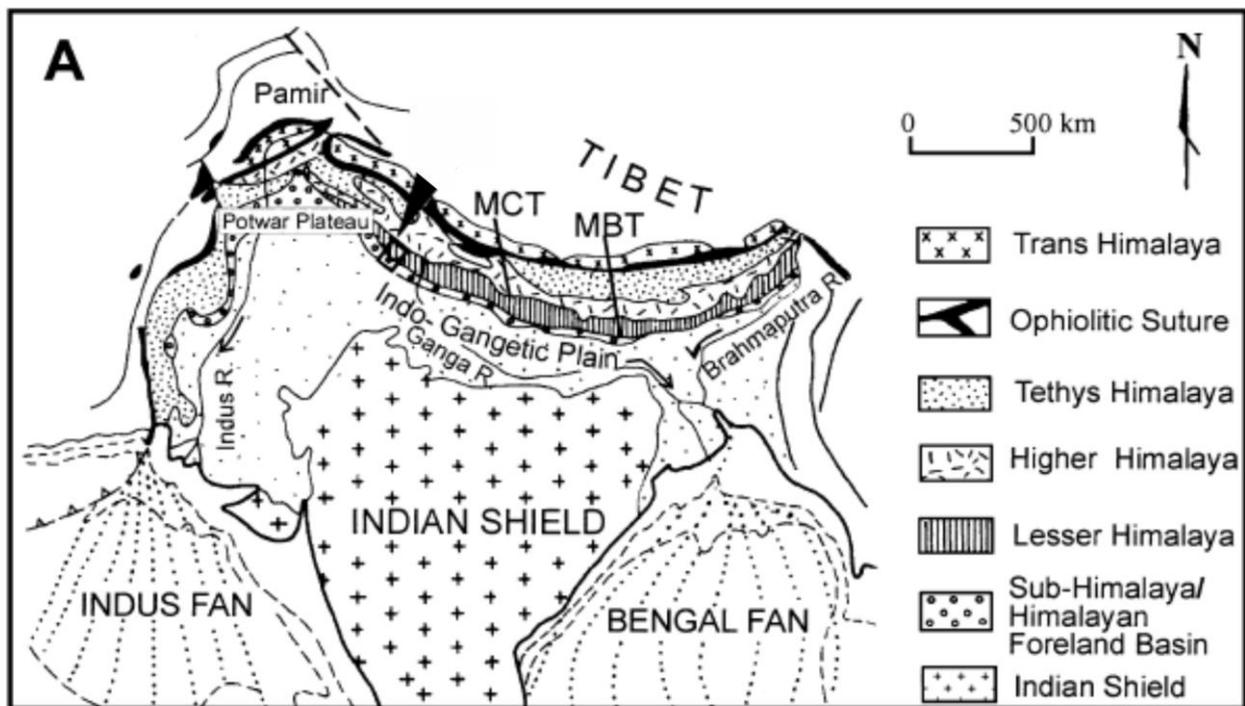


Figure 3 Simplified geologic map of the Himalayan Range, Indian shield and the surrounding area. The map shows the lateral distribution of Himalayan Foreland Basin between the Indus and Brahmaputra rivers and the tectonic regime of the area. MCT= Main Central Thrust; MBT= Main Boundary Thrust. (Kumar et al., 2003)

The Himalayan Foreland Basin is interpreted to have formed in response to the initial collision of India with Eurasia during Late Paleocene to Early Eocene (Acharryya, 2007; Singh, 2008; Powers et al., 1998) and to downward flexure of the Indian plate caused by the large crustal load of the evolving Himalaya (Kumar et al., 2003).

Within the Southern part of the Himalayan Foreland Basin, the Precambrian basement (High Himalaya) and a relatively complete cover of Phanerozoic rocks (Tethys Himalaya) were thrust

southward over a discontinuous sedimentary sequence along the Main Central thrust (Figure 3). The Precambrian and younger rocks of the High and Tethys Himalaya were originally part of India's northern passive margin. South of the Main Central thrust, Proterozoic and younger rocks of the Lesser Himalaya are thrust southward over the Miocene to Pleistocene Siwalik group along the Main Boundary thrust (Figure 4). Deformation on the Main Boundary thrust began before 10 Ma and continues today (Powers et al., 1998).

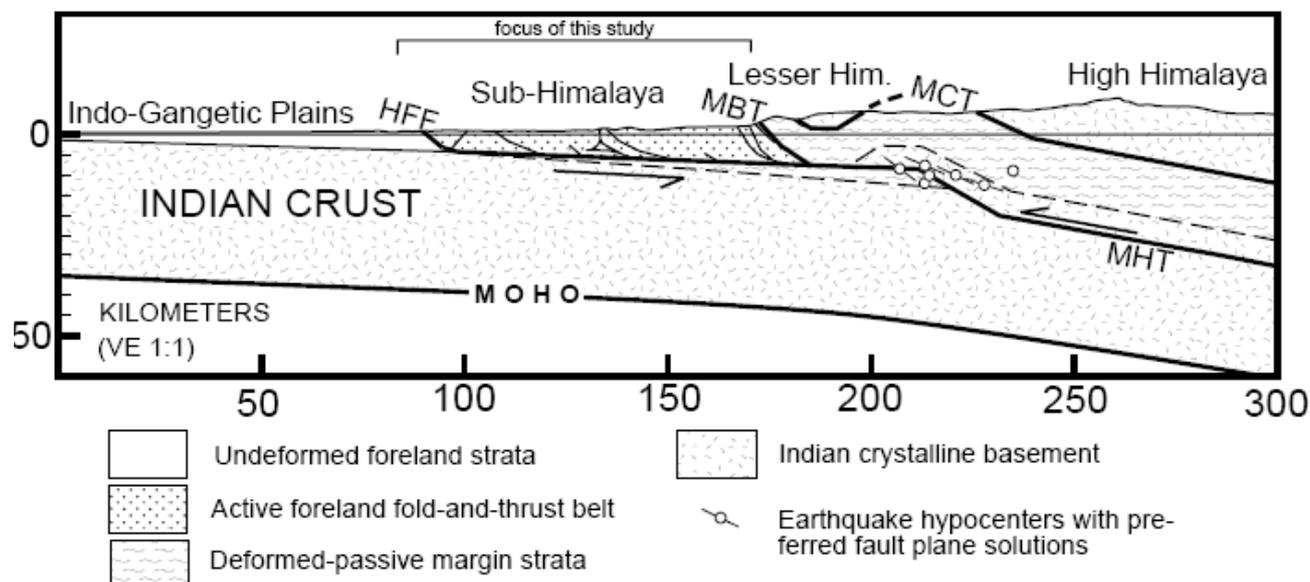


Figure 4 Schematic crustal-scale section of the Himalayan collision zone. Principal Himalayan tectonostratigraphic units are bounded by the Himalayan Frontal fault (HFF), the Main Boundary thrust (MBT), and the Main Central thrust (MCT). Note the Passive margin (Vindhyan) strata atop the Indian shield and beneath the Sub- and Lesser Himalaya (Powers, Lillie, & Yeats, 1998)

At present, the Indian craton is moving NNE at a rate of 50 mm/yr relative to the Eurasian plate (Figure 5). As the Indian plate underthrusts the Himalaya, it warps down in response to an advancing orogenic load. Molasses of the Siwalik Group occupy the resultant basin. Siwalik strata are time transgressive and have progressively lapped onto the Indian craton with continued convergence. South of the Main Boundary thrust, numerous faults displace the Siwalik strata; the southernmost is termed as the Himalayan Frontal Fault. The Himalayan Frontal Fault cuts the Siwalik strata in places at the surface, but it is often a blind thrust; strain release is thus expressed in anticline growth. Structures within the Sub-Himalaya are consistent with thin-skinned fold and thrust deformation above a gently dipping detachment (Powers, Lillie, & Yeats, 1998).

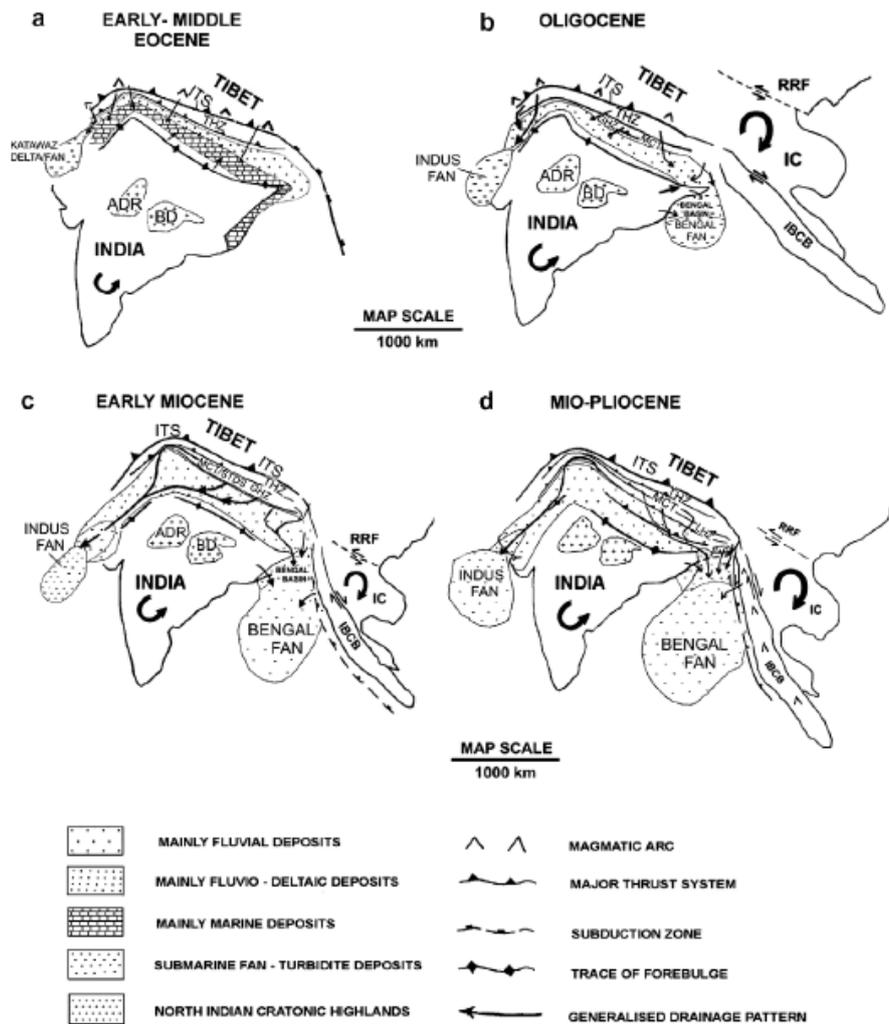


Figure 5 Schematic paleotectonic maps of India and its neighbors. Setting of Himalayan Foreland Basin and related basins are shown. Himalayan Foreland Basin is placed between forebulge and foredeep. Abbreviations: ADR – Aravalli–Delhi Range, BD – Bundelkhand Granite, GHZ – Grate Himalayan zone, IC – Indochina block, IBCB – Amalgamated Indo–Burma and Central Burma Block, ITS – Indus Tsangpo Suture, LHZ – Lesser Himalayan zone, MCT – Main Central Thrust, RRF – Red River Fault, STDS – South Tibetan Detachment system, THZ – Tethyan Himalayan zone (Acharrya, 2007).

The Himalayan tectonic activity is ongoing. It causes subsidence of the foreland basin and exerts an ultimate control on sediment accumulation over periods of tens of millions of years (Gibling et al., 2005). Sediment accommodation in the basin was controlled primarily by flexural subsidence driven by the topographic load of the thrust belt and sediment loads in the foreland. It was also affected by regional isostatic uplift during erosion of the orogenic belt, and by uplift associated with advancing thrust wedge or retrograde migration of the forebulge (Kumar, Ghosh, Mazari, & Sangode, 2003).

The Himalayan Foreland Basin comprises a number of sub-basins developed in various sedimentary environments during the Plio-Pleistocene phases of Himalayan orogeny (Kumar et al., 2003). These sub-basins were formed by several basement highs, separated from each other by preexisting lineaments. These lineaments are extensions of basement features from the Indian shield into the Himalaya. They formed as normal faults during the tensional regime and were later reactivated as thrust faults during the Tertiary Orogeny. These faults did not only control the thickness of the sedimentary succession but also the sedimentation pattern (Kumar, Ghosh, Mazari, & Sangode, 2003). One of the sub-basins is the Ganga Foreland Basin, where the study area is located. This basin will be studied in detail in the following paragraphs.

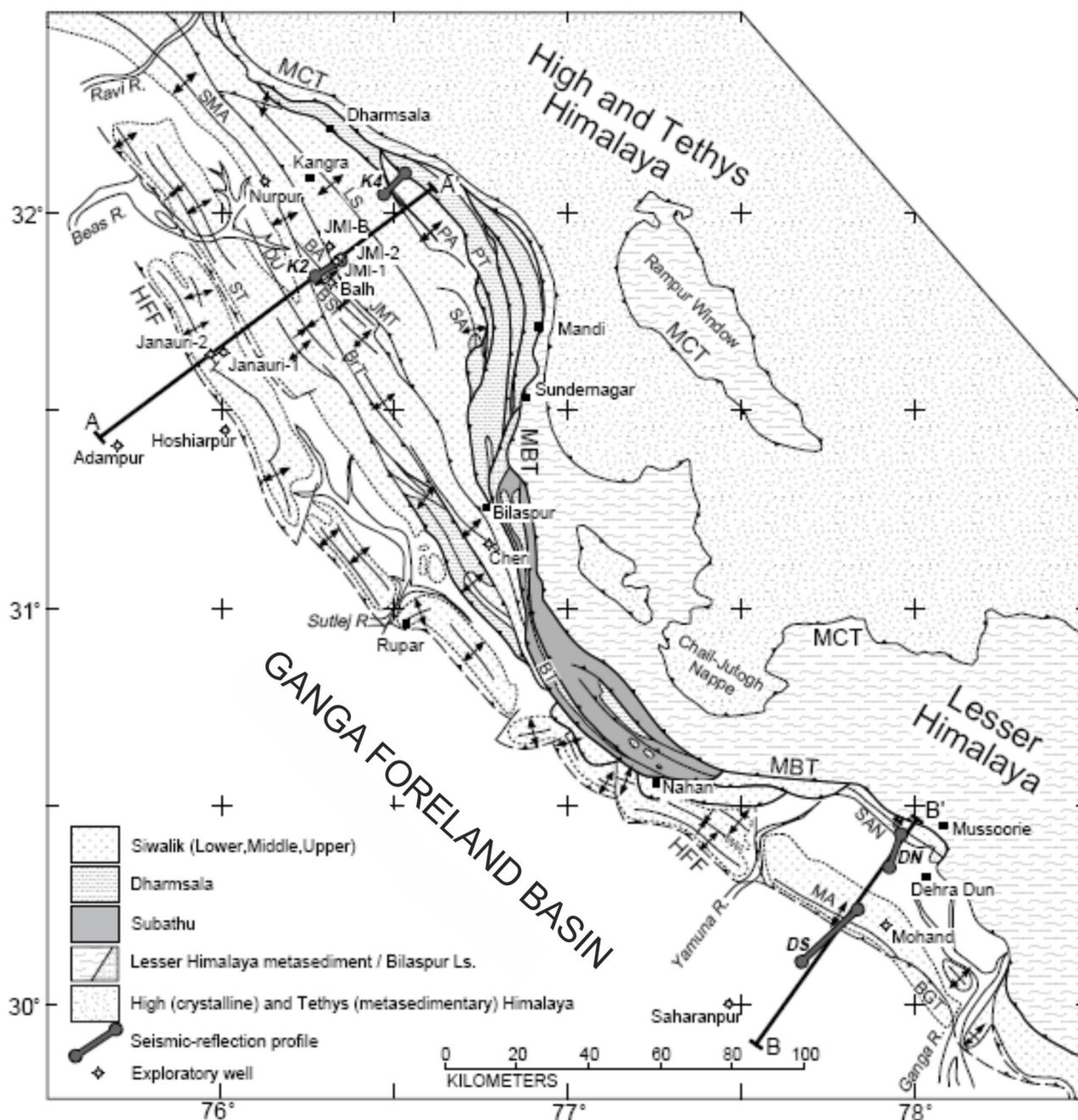


Figure 6 Location of the Ganga Foreland Basin, with respect to the Himalayan Foreland Basin. This geologic map of part of the Sub-Himalaya shows balanced sections, seismic profiles, and drill holes. Note the great variation in the width of the Sub-Himalaya (MBT to HFF) due in large part to the sinuous surface trace of the MBT. Structures: BA—Balh anticline, BGT—Bhingoda thrust, BrT—Barsar thrust, BS—Balaru syncline, BT—Bilaspur thrust, DU—Dumkhar syncline, HFF—Himalayan Frontal fault, JMT—Jawalamukhi thrust, LS—Lambargaon syncline, MBT—Main Boundary thrust, MA—Mohand anticline, MCT—Main Central thrust, PA—Paror anticline, PT—Palampur thrust, SA—Sarkaghat anticline, SAN—Santaurgarh anticline, SMA—Suruin-Mastgarh anticline, ST—Soan thrust. Seismic-reflection profiles: DN—Doon-N, DS—Doon-S, K2—Kangra-2, K4—Kangra-4. (Powers, Lillie, & Yeats, 1998)

Stratigraphy of the Himalayan Foreland Basin

The Paleocene sedimentation in the Himalayan Foreland Basin was nearly without break, strikingly similar and laterally extensive. Rock formation during the Eocene was associated with volcanism, possibly caused by slab break of thermal anomaly following collision and movement along some deep faults (Acharyya, 2007).

The stratigraphy of the Himalayan Foreland Basin is demonstrated in Figure 7. The Himalayan Foreland Basin succession coarsens upward from the Paleocene shallow marine flysch sediments to the Plio-Pleistocene terrestrial molasse deposits. The Upper Paleocene to Upper Eocene Subathu Formation is composed of mudstone and sandstone with minor limestone. The Upper Eocene to Miocene Dharamsala Formation conformably overlies the Subathu Formation and is the stratigraphic equivalent of the Dagshai and Kasauli formations in the Simla Hills. These comprise dominantly shallow marine to continental sandstone and mudstone strata. The terrestrial molasse deposits, the Siwalik Group (Middle Miocene- Pleistocene), are present in the southern part of the foreland basin. The sedimentary succession of the Siwalik Group, well known for its abundant vertebrate fossil assemblages, has been divided into three lithostratigraphic units: Lower, Middle and Upper Siwalik. The Siwalik molasses thin to the south and coarsens upward from mudstone-sandstone (Lower Siwalik), to sandstone dominated (Middle Siwalik), to conglomerate, sandstone and mudstone (Upper Siwalik) facies. The Upper Siwalik succession varies laterally across the foreland basin exhibiting an increase in conglomerate towards the Main Boundary Thrust. The Lower Siwalik and older strata are typically well indurated, whereas the Middle and Upper Siwalik strata are normally friable. The Siwalik Group is overlain by Quaternary conglomerates in broad synclines, like the Dehra Dun Reentrant and the Indo-Gangetic Plain, south of the Himalayan Foreland Basin (Kumar, Ghosh, Mazari, & Sangode, 2003).

AGE	LITHOLOGY	FM	DESCRIPTION	VELOCITY (m/s)	THICKNESS (m)
PLEISTOCENE		Neogal	Conglomerate of plains and duns; river terraces and glacio-fluvial deposits of foothills		
PLIOCENE		Upper Siwalik	Conglomerate with increasing sandstone away from MBT; some calcite cementation; clay and siltstone interbeds	2500	2300
MIOCENE		Middle Siwalik	Sandstone with minor claystone; conglomerates prominent closer to MBT; appearance of kyanite as marker	3500	2000
		Lower Siwalik	Alternations of sandstone and claystone with minor siltstone and pebble horizons	4000	1300
		Upper Dharmasala	Greenish gray sandstone with minor claystone	4100	1300
OLIGOCENE		Lower Dharmasala	Purple clay and siltstone with minor sandstone	4300	1300
EOCENE		Subathu Group	Red and green nummulitic shale, minor limestone and sandstone	4300	1500
PALEOCENE		Singtali Fm.	Limestone		50+
CAM-BRIAN		Vindhyan Group	Sandstone, siltstone, and limestone, some weakly metamorphosed	4400+	
PRE-CAMBRIAN		Delhi and Aravalli Groups	Calc and garnet schist, arkosic sandstone, and marble		

Figure 7 Generalized stratigraphy of the Himalayan Foreland Basin in India (Powers, Lillie, & Yeats, 1998)

Tectonic evolution of the Ganga Foreland Basin

The Ganga Foreland Basin, the largest active foreland basin of the Himalaya, developed on an old, cold and rigid Indian lithosphere showing high variability in the down-flexing characteristics (Singh, 2008). In the beginning of Quaternary, the region in front of the Himalayan Siwalik Basin that was an elevated landmass started subsiding and forming the Ganga Foreland Basin. The resulting rather asymmetrical foreland basin now supports a large thickness of alluvial sediments (Mahadevan, 2002). The fluvial geomorphic features often exhibit tectonic control and evidences of active tectonics (Singh, 2008). In general, during the development of the basin, the rate of downflexing of the lithosphere was low, while sediment supply was high, although gradually decreasing (Mahadevan, 2002). No marine incursion from the Bay of Bengal could enter deep into the Ganga Foreland Basin. Consequently, deposition in the basin took place exclusively by fluvial processes, 100-200 m above the sea-level (Gibling, Tandon, Sinha, & Jain, 2005).

The Ganga Foreland Basin exhibits all the important components of a foreland basin, namely orogen (Himalaya), deformed foreland sediments (Siwalik), active foreland (Ganga Plain) and peripheral bulge (Bundelkhand Craton) (Singh, "Inception, sedimentation and deformation of Ganga Foreland Basin", 2008). The varying thicknesses of the alluvial fill in the basin shows control of the basement highs (Singh, 2008), which were initially responsible for the formation of the Ganga sub-basin (Kumar, Ghosh, Mazari, & Sangode, 2003). Under this cover of alluvium lies a deep structural trough, having WNW-ESE trend and a general slope of 1 to 3 degrees from south to north. A few transverse ridges are also present in this basement (Mahadevan, 2002).

One can identify three distinct zones from north to south within the Ganga Foreland Basin (Figure 8). The Piedmont zone is located adjacent to the Siwalik Hills and slopes southward (Figure 9). It is essentially in contractional tectonic regime, showing features like thrusts dipping northward, conjugate system of strike-slip faults (NNE-SSW and NW-SE), linear-ridges, warping and deeply incised river channels (Singh, 2008).

The Central Alluvial Plain is characterized by NW-SE, WNW-ESE and W-E trending lineaments, which have controlled the positioning of most of the river. Entrenchment of river channels within their river valleys is very prominent, often making cliffs along the river channels (Singh, 2008).

The Marginal Alluvial Plain comprises the southernmost part of the Ganga Plain, located south of the axial river up to the craton margin. It shows rivers flowing in SW-NE direction, which become almost W-E in its northern part. This region shows the development of gravity faults and graben-like structures causing highly variable sediment thickness over a short distance. Main tectonic trend in this area is SW-SE (Singh, 2008).

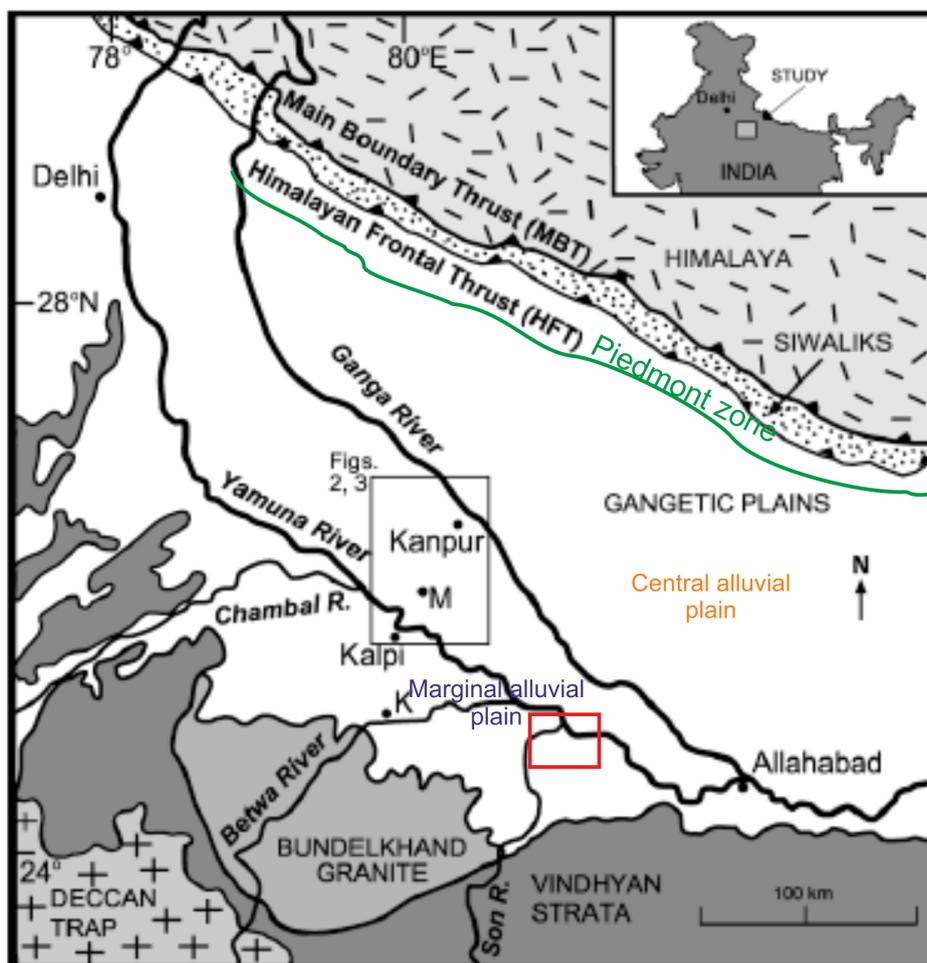


Figure 8 The Ganga Foreland Basin and its different zones and characteristics. The Ganga and Yamuna rivers rise in the Himalaya and curve eastwards to form axial drainage lines within the Himalayan Foreland Basin. Northward-flowing rivers from the Indian Craton join the axial systems. (Gibling, Tandon, Sinha, & Jain, 2005).

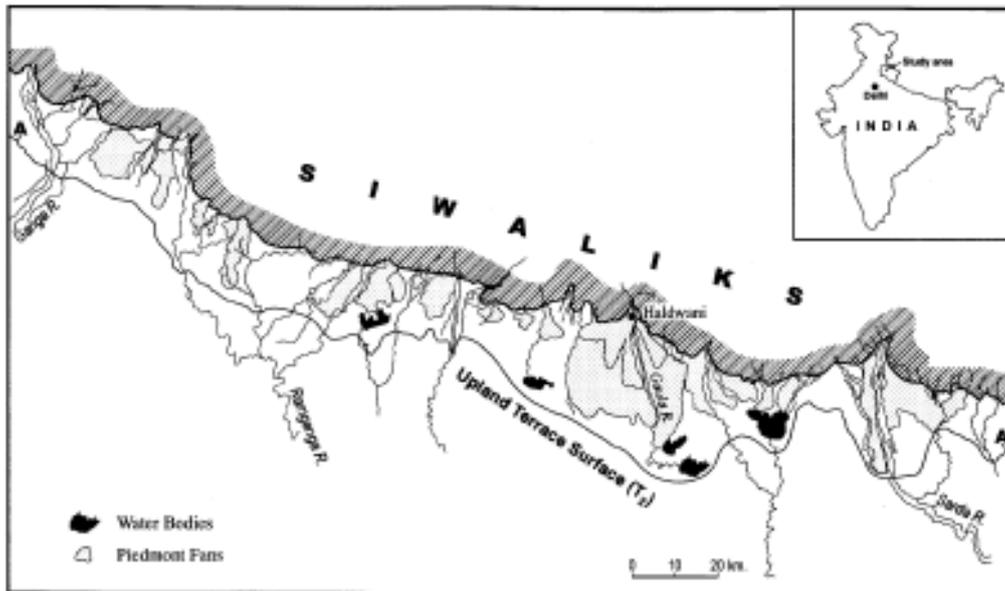


Figure 9 Schematic geomorphic map of Siwalik and Piedmont zone (the northernmost part of the Ganga Foreland Basin). The line A-A' marks the limits of the Piedmont zone, attached to the Southern part of the Siwaliks (Shukla & Bora, 2003).

The pattern and orientation of tectonics varies from the Himalayan Orogen to the Craton margin in the form of compressional tectonics to extensional tectonics respectively. The Craton margin exhibits prominent tectonic movements manifested in the form of vertical uplift, kilometer-scale warping, tilting of blocks, conjugate fractures and gravity faults. A tectonic event, dated 8-5 kA disrupted number of drainages, converting channels into linear lakes and produced an undulating topography (Singh, 2008).

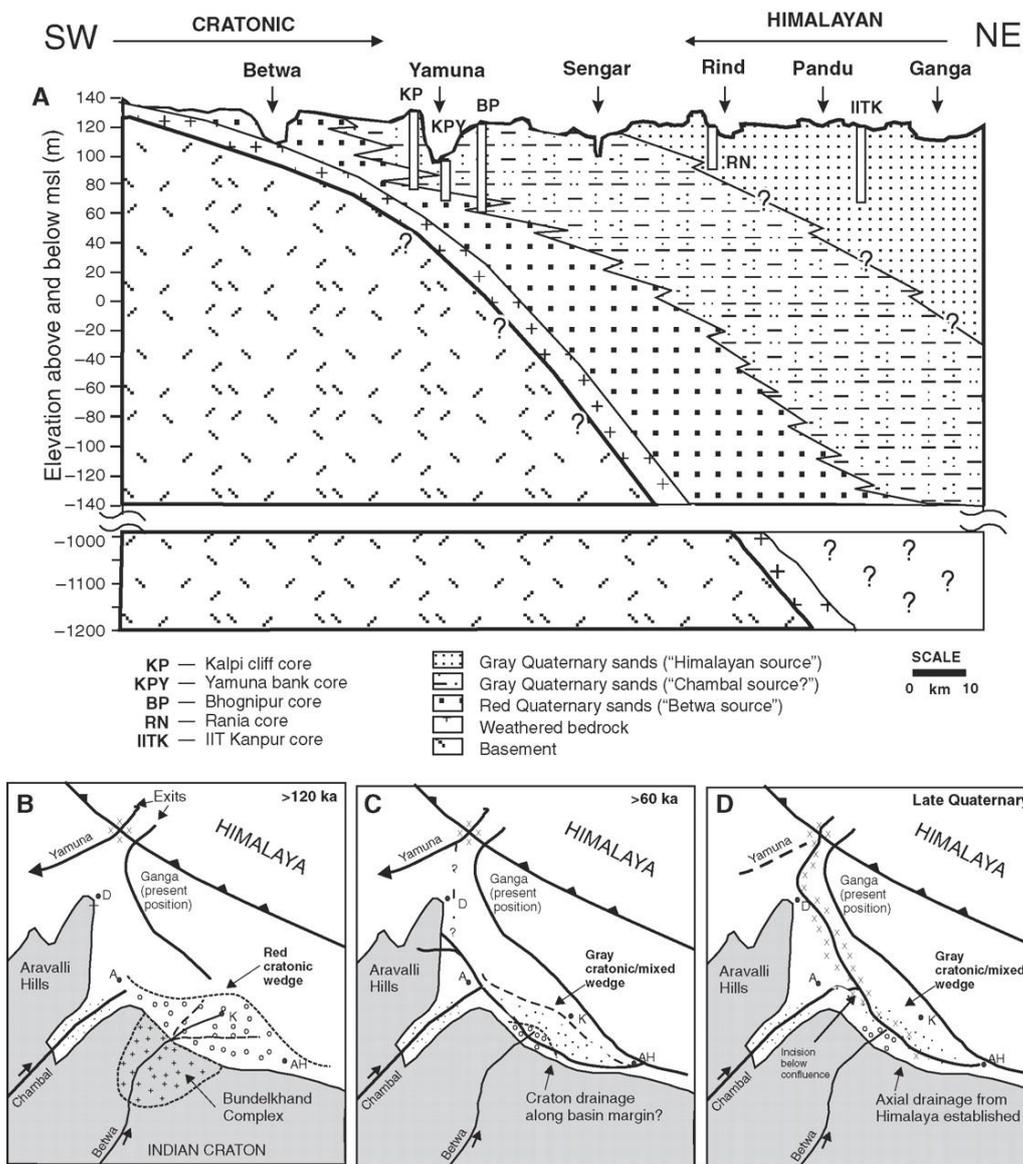


Figure 10 Tectonic and geological framework of the southern part of the Ganga Foreland Basin. The effect of cratonic basement and active tectonics had been strong during the development and sedimentation pattern of the basin (Singh, 2008).

Initially the Ganga Foreland Basin was rather narrow, but it increased in its width with time, by gradually expanding over the southern craton (Figure 10). The last major southward expansion of the basin is probably related to uplift and thrusting of Upper Siwalik in middle Pleistocene. The southward expansion of the foreland basin is about 100 km since then. The southward (cratonward) migration of the basin caused onlap of Himalayan derived sediments (micaceous litharenite) over the craton-derived sediments (subarkose), which make a thin veneer over the basement rocks. The Indian lithosphere beneath the Ganga Foreland Basin shows much inhomogeneity in the form of basement highs and lows. Important basement highs are the Delhi-Haridwar Ridge, Faizabad Ridge, Mirzapur-Ghazipur Ridge and Munghyr-Saharsa Ridge. There are also a number of basement faults, namely the Moradabad Fault, Bareilly Fault, Lucknow Fault, Patna Fault and Malda Fault (Singh, 2008).

In Bihar, synchronous with the rifting and growth of the Ganga Foreland Basin in the North, the Chotanagpur Plateau (an important geomorphic feature located within Bihar and southern of the Ganga Foreland Basin) registered episodic uplifts, largely epeirogenic. These uplifts enhanced periodically the rigors of erosion leading to the formation of more than one plain surface. The lateritic cover formed during the late Cenozoic on the more or less stable main land of Bihar was eroded during a period of stability. The current manifestation of Chotanagpur

Plateau tectonic activity is the seismicity of the area as well as the presence of several hot springs along reactivated lineaments (Mahadevan, 2002).

The subsidence of the Ganga Basin is continuing today, probably as an adjustment to the Himalayan Orogeny and accounts for the present day seismicity of the region (Mahadevan, 2002).

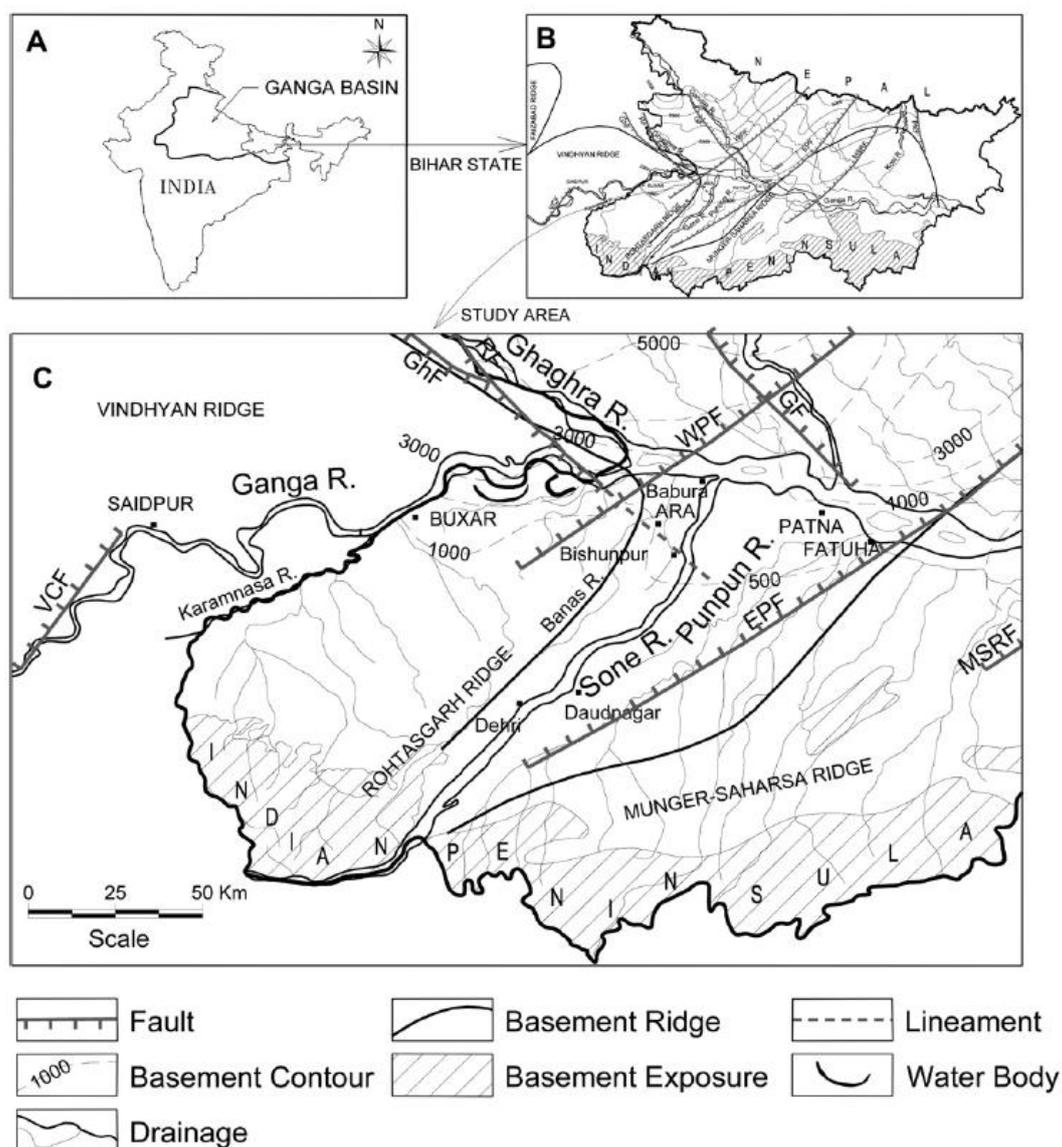


Figure 11 Geomorphologic and tectonic characteristics of Patna and Bhojpur district (Sahu, Raju, & Saha, 2010).

Regarding the evolution and active tectonics of the area surrounding Maner, which is also the focus of this research, geomorphic developments and sedimentation patterns have been related with the movements along East Patna Fault (EPF) and West Patna Fault (WPF), which can be seen in Figure 11. These tectonic movements have proved to have affected the course of both the Ganga and the Sone River. Both faults are transverse to the Himalaya and cut across the Ganga River in a NE-SW direction. Tectonic activity of these two major features led to uplift, followed by tilting of the block between them towards the NW. The Sone River, lying laterally close to the line of uplift, has undergone avulsions at different times of tilting, whereas the Ganga River located at the lower parts of the tilting-block away from the line of uplift has migrated in the down-tilt direction (Sahu, Raju, & Saha, 2010). The migrating course of the Sone River is shown in Figure 12.

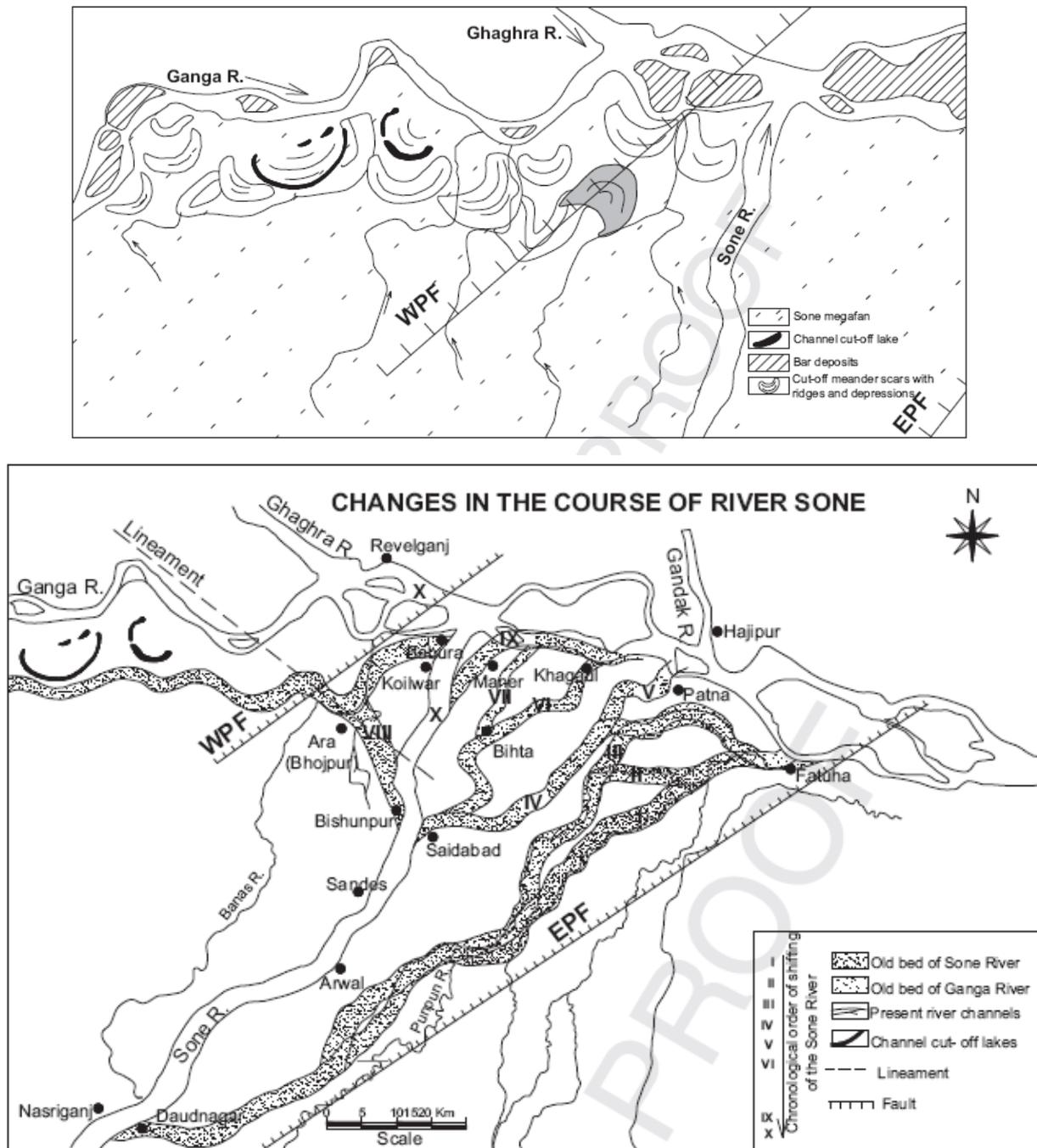


Figure 12 Maps that show oxbow lakes from the meandering course of Ganga River (top) and the laterally migrating course of Sone River; Maner block (Sahu, Raju, & Saha, 2010).

The Sone River, owing to its location, has experienced maximum tilting and has consequently deflected its channel several times westwards, in a NW direction from its earlier ENE direction of flow. The present channel course might have resulted due to migration of the Ganga further north, to valley entrenchment and consequent slope creation (Sahu, Raju, & Saha, 2010).

The Ganga River, being located at the distant parts of the hanging block, away from the uplifts of EPF, has experienced lower tilt rate, causing migration of river channel (Sahu, Raju, & Saha, 2010). This migration of the river channels has led to formation of oxbow lakes and other sedimentary features (Figure 12). Most of the lakes are at present in advanced stage of siltation (Singh, 2008).

Stratigraphy of the Ganga Foreland Basin and Bihar

The oldest rocks so far detected in Bihar state are those of what are termed as the Older Metamorphic Group found as enclaves in a vast mass of granitic rocks, named the Singhbhum Granite. The early exposed crust of south Bihar may be divided into two main domains, namely an older Archean-Proterozoic domain (~ 3.5-1.6 Ga), which is mainly encountered in the southern parts of the state and a domain that comprises largely of Proterozoic rocks and covers a major part of the northern part of Bihar. Those domains are designated as Singhbhum Greenstone-Granite Domain (SGGD) and Chotanagpur Granitic Gneiss Complex (CGGC), respectively (Mahadevan, 2002).

In the north of the Ganga Foreland Basin, Quaternary sediments lie over the fringes of the Precambrian shield. Siwalik formations of Miocene to Pliocene age are encountered along the Himalayan front and in the deeper part of the foreland basin. Outcrops of the Upper Siwalik formation emerge out of the alluvial cover along the Himalayan foothills. They comprise boulder beds, conglomerates, carbonate, greywacke, arenites and agillites (Mahadevan, 2002).

Extensions of the Bijawars, Vidhyans and Gondwana Formations are encountered frequently in outcrops in the Ganga Foreland Basin and form an important part of the stratigraphic succession underlying the Ganga alluvium (Mahadevan, 2002). The stratigraphy of the Ganga Foreland Basin is illustrated in Table 1.

Quaternary sediments (Table 1) have been deposited along the northern fringes of the Chotanagpur uplands. Southern to the uplands, there is a pediplane covered by reddish regolith, followed further north by terraces of Older Alluvium. The Older Alluvial Group comprises oxidized red brown clays, silt and sand with profuse calcareous nodules and pisolithic iron concentrations. This group is succeeded by thin Loess-like aeolian deposits in several parts of the Central Bihar Basin, which are not encountered in the study area. After these deposits, lies the more dominant Newer Alluvial Group, which forms lower terraces and has a distinctive though sometimes overlapping lithology comprising unoxidized pale greyish yellow to brown silt, clay and sand. Present day sediments consist of unoxidised sand, silt and clay intrusions into the younger alluvium along stream courses, channels, levees and swamps. Among the still younger sequence, an older floodplain has been distinguished from present day flood plains in several areas that represent the past and present oscillation limits of the Ganga and its tributaries. The youngest sediments in the Ganga Foreland Basin are the recent deposits of clay and silt, called the Diara formations. These younger formations are less oxidized and are loose or less compact, with a high content of carbonaceous matter that makes them look gray or black. They are also more porous and water bearing. The Older Alluvial Group is generally placed in the Middle Pleistocene, the Newer Alluvial Group in the Upper Pleistocene to Holocene and the Older and Younger Floodplain deposits in the Early Holocene to the Present (Mahadevan, 2002; N. Dayal and R.S. Sahu, pers. comm.).

		AGE (Ma)		Stratigraphy		
		RECENT (QUATERNARY)		ALLUVIUM		
		PLEISTOCENE (5.0)				
CENOZOIC	NEOGENE	PLIOCENE		SIWALIK	UPPER SIWALIK	
		MIOCENE	UPPER		MIDDLE SIWALIK	
			MIDDLE		LOWER SIWALIK	
			LOWER (23.5)		MATERA Fm.	
	PALEOGENE	OLIGOCENE				
		L. PALEOCENE				
MESOZOIC			CRETACEOUS			
			JURASSIC		PURNEA MEGA SEQUENCE	U. GONDWANA
			TRIASSIC			L. GONDWANA
PALEOZOIC			PERMIAN (29.5)			
			CARBONIFEROUS			
			SILURIAN			
			ORDOVICIAN - DEVONIAN			
	CAMBRIAN			LATE	UPPER VINDHYAN	
		MIDDLE				
		EARLY (590)	PURANPUR MEGA SEQUENCE	GANDAK SEQUENCE		
PROTEROZOIC			VENDIAN (680)		PURANPUR MEGA SEQUENCE	MADHUBANI SEQUENCE
	RIPHEAN	LATE (1150)		LOWER VINDHYAN		JAGADARI SEQUENCE
		MIDDLE (1350)				
		EARLY (1450)				
			LOWER PROTEROZOIC (2500)		BIJAWAR FORMATION (METAMORPHICS)	
		ARCHEAN		GRANITIC GNEISSES BASEMENT		

Table 1 Stratigraphy of the Ganga Foreland Basin (Mahadevan, 2002)

In the Sone-Ganga alluvial tracts in the West, the upper Mohanapur Formation and the underlying Lower Mohanapur Formation constitute the Older Alluvium Group forming the higher terraces and the Bare Formation the Newer Alluvium Group, forming the younger terraces. The next younger group of sediments consists of the Kudra Formation, which is made up of a Lower Ramgarh Old Floodplain and the upper Durgauti Formation of channel deposits. Locally an aeolian deposits horizon is encountered, which is part of the Bare Formation and is labeled as the Hanumangarh Formation. Present day sand dunes are also known, especially along the right banks of the Sone River (Mahadevan, 2002)

The Diara formation (Figure 13) is of great interest to this research, since it largely comprises the first decades of meters of the Holocene and refers to Ganga alluvial deposits, which according to previous research (Central Ground Water Board, 2010; Saha, Sahu, & Chandra, 2010) have been identified as layers containing high levels of arsenic.

MIDDLE GANGA BASIN QUATERNARY STRATIGRAPHY

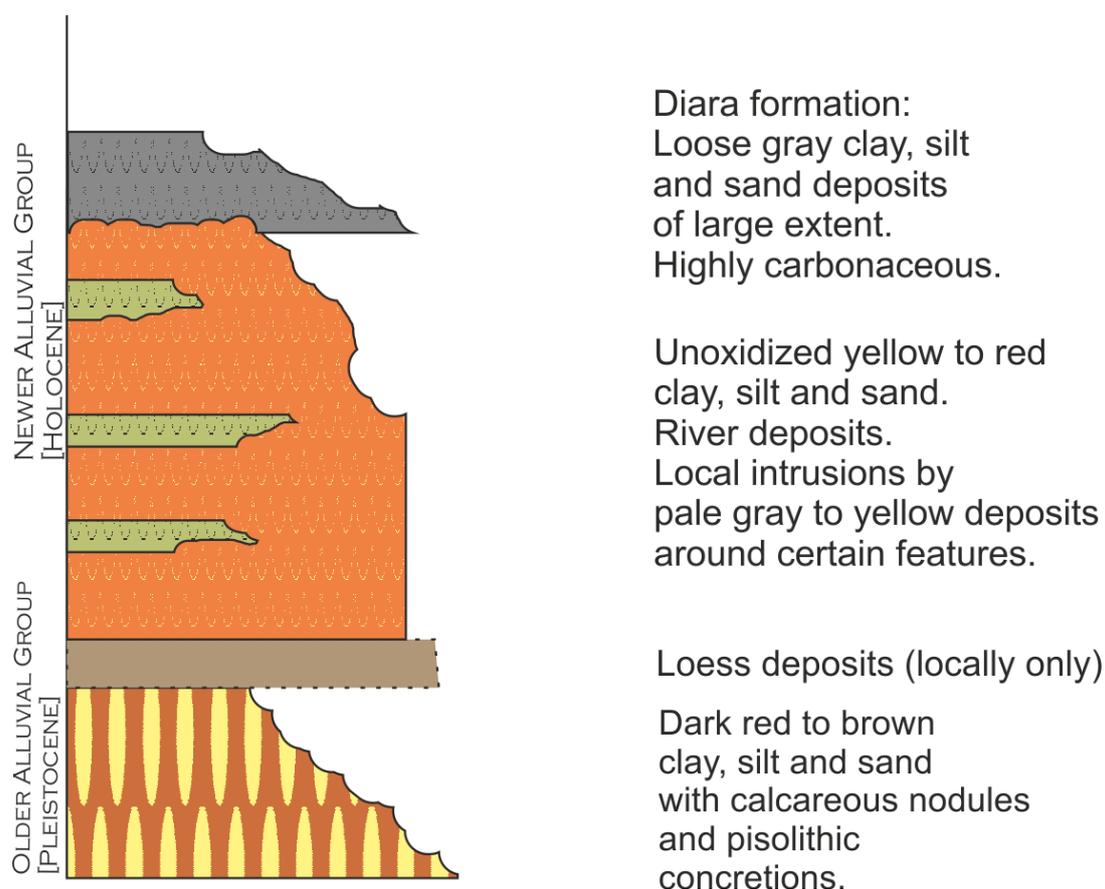


Figure 13 Middle Ganga Basin Quaternary stratigraphy, designed according to the descriptions and tables that are included in (Mahadevan, 2002)

Figure 14 gives a more detailed description of the Newer Alluvium and the Older Alluvium in Bhojpur district, western to Maner block and by the Sone River. As observed in the cross-section, the area close to Maner, which is where the present research area is located, consists of mainly fine and more rarely medium sand which progressively becomes coarser to the bottom and contains gravels as well. The shallow parts (possibly Diara formation) are intercalated by silty and sandy clay (Saha, Sahu, & Chandra, 2010; Central Ground Water Board, 2010; Mahadevan, 2002).

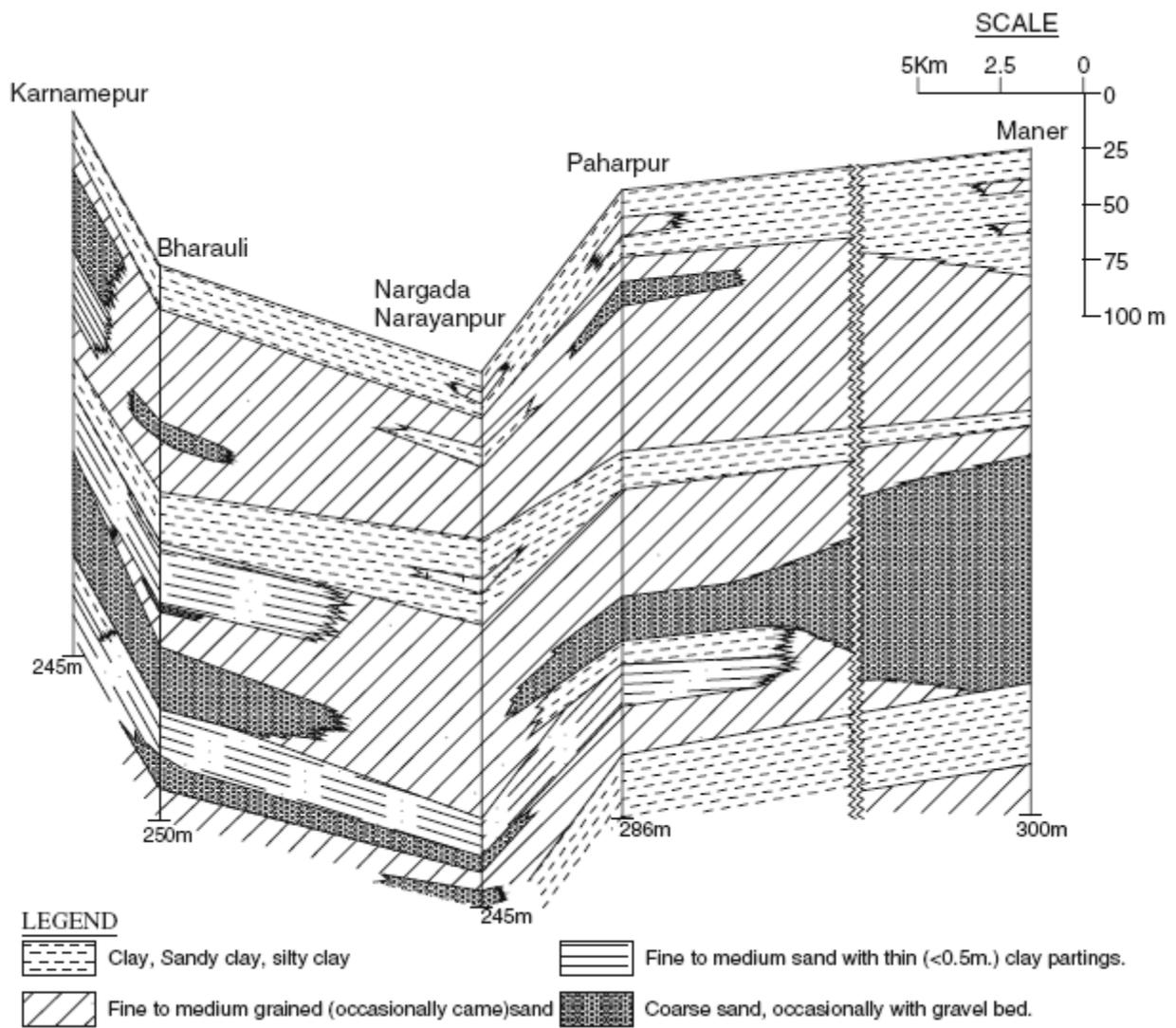


Figure 14 Cross section that illustrates the Quaternary stratigraphy of Bhojpur. The area of interest is Maner. The thickness of alluvial deposits is very large (Saha, Sahu, & Chandra, 2010).

Fluvial architecture and depositional pattern in the Ganga Foreland Basin

The Ganga Foreland Basin shows a diverse fluvial landscape of Late Quaternary age with a variety of fluvial systems (Sahu, Raju, & Saha, 2010; Singh, 2008).

Present-day surfaces of the Ganga Foreland Basin exhibit many distinctive fluvial geomorphic features. Several distinct regional geomorphic surfaces are identified which have been formed under changing climatic and tectonic conditions of late Pleistocene- Holocene (Singh, 2008). The following table gives a short explanation of floodplain terminology, according to (Gibling, Tandon, Sinha, & Jain, 2005)

Floodplain terminology	Definition
Interfluve	Area between two rivers, especially the relatively undissected upland or ridge between two adjacent valleys that contain streams flowing in the same general direction.
Active Floodplain	An overflow surface that is periodically constructed and possibly eroded by the adjacent river but is undergoing net growth during the “present time” (past 10 years or so).
Inactive Floodplain	An area adjoining a river that is inundated so rarely that it is no longer actively growing by present alluvial processes.
Alluvial Terrace	Typically a long, narrow, relatively level surface, generally less broad than a plain, composed of unconsolidated alluvium; usually a valley-contained aggradational form produced by renewed downcutting of the floodplain or valley floor by a rejuvenated stream.
Attached and Detached Plains	Major drainage axis inundates a broad interfluve sufficiently frequently to promote aggradation over wide areas (attached plain), or infrequently or not at all (detached plain). In the latter case, the plain may develop an extensive degradational surface, or small rivers, lakes and eolian dunes may aggrade locally. Detachment may reflect incision of major drainage axes or reduced flow. Term applicable over timescales of 10 ³ to 10 ⁴ years.
Aggradation/Degradation Rhythms	Discontinuity-bounded (allostratigraphic) units that form a prominent motif in floodplain deposits of the southern Gangetic Plains. Thick, coherent floodplain deposits alternate with thinner zones containing one or more discontinuities.

Table 2 General floodplain terminology and definitions. (Gibling, Tandon, Sinha, & Jain, 2005)

These modern interfluves (Figure 15) of the southern part of the Ganga Foreland Basin are not presently inundated by the major Himalayan and cratonic rivers, which are incised within narrow active floodplains. Late Quaternary strata below the interfluves show a distinctive architectural motif of discontinuity- bounded sequences, as the following illustration shows (Gibling, Tandon, Sinha, & Jain, 2005).

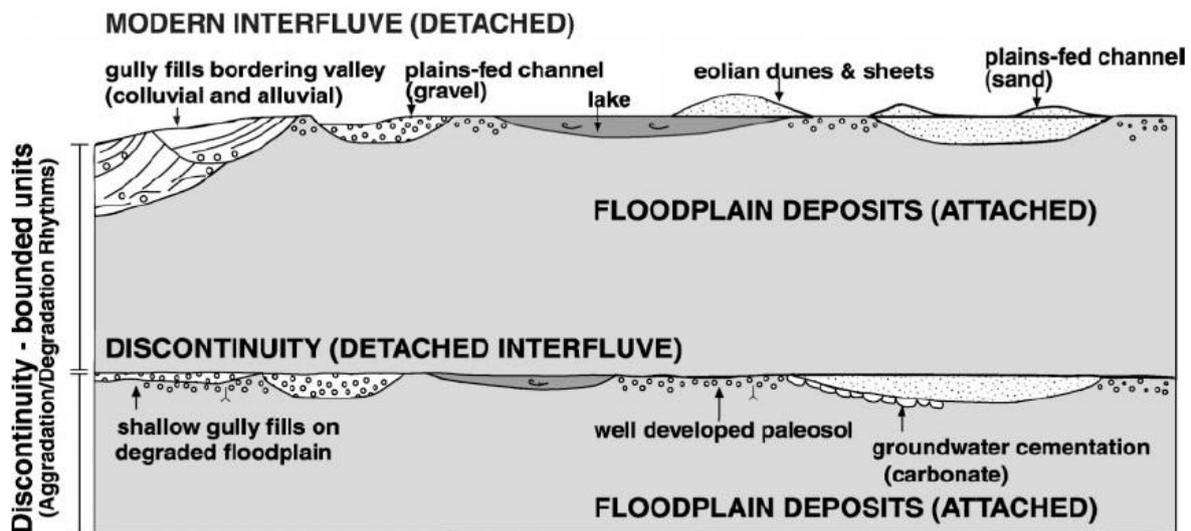


Figure 15 Stratigraphic model for modern interfluves and inferred paleo-interfluves in the Southern Gangetic Plains. The terms "attached" and "detached" refer to the degree of attachment of parts of the interfluves to the major drainage axes (Gibling, Tandon, Sinha, & Jain, 2005).

The sequences record periods when floodplains were inundated by major rivers and experienced sustained aggradation (Figure 16). Declining flood frequency on parts of the interfluves resulted in low-relief degradation surfaces and badland ravines, as well as local soil development and sediment redistribution within plains-fed rivers, lakes, and Aeolian dunes. Age dates below the interfluve surface suggest that river and floodplain behavior primarily reflect variation in intensity of the Southwest Indian Monsoon. Discontinuities at deeper levels can be linked to tectonism (Gibling, Tandon, Sinha, & Jain, 2005).

The active tectonics of Holocene in the Ganga Plain has strongly controlled the regional patterns of fluvial facies and sediment transfer (Singh, 2008). The present-day active rivers show the strong effect of tectonics in the form of distorted channel segments, uneven height of cliffs along the valley margin. There are distinct zones that reflect the influence of more intense tectonism in the form of warping. The southern part of the Ganga Plain shows several well-defined belts of intense and closely-spaced warping along the river channels. Tectonic lineaments are mostly well-defined, while at few places evidence of faulting is also present (Singh, 2008). This region shows strong incision of channels, conjugate sets of fractures, bending, tilting, updoming of sediments, and formation of triangular facets in the cliff section and is characterized by extensional tectonics. Vertical uplift of the region is also prominent. An important event of active tectonics has produced tens of kilometer-scale undulations in the Ganga Plain. This tectonic event shaped the fluvial landscape, and many present-day geomorphic features are related to this event. The warping of the alluvial surface on tens of kilometers scale caused disruption of small tributaries and formation of linear lakes. Later, these linear lakes changed to smaller ponds arranged in linear cluster. Areas of centripetal drainages with ponds and lakes developed on a large scale. It also caused uplift of the river channel margins (cliffs) by few meters. These river channel margin areas show presently intense gullying, which was initiated around 5 ka BP (Singh, 2008).

The depositional pattern of the Ganga Plain can be classified into two main areas. The Piedmont zone shows mostly deposition of conglomerate and coarse-grained sand in braid plain. Role of debris flow is very limited. The vast area of the Central Alluvial Plain was deposited mainly under the influence of a number of megafan systems, with specific facies development. At present, the Central Alluvial Plain shows deposition in the channel-flood plain. The channels are incised, so they would produce multistoried sand bodies. The vast interfluve areas are beyond the reach of floods of active channels and make a distinctive lithofacies association of muddy

sediments deposited mainly by sheet flow and related processes. These muddy deposits are designated as interfluves (Singh, 2008).

Facies	Description	Interpretation
Floodplain Deposits	Locally .10 m thick, with decimeter to meter scale bands. Red- to yellow-brown stiff silt-clay, with minor organic matter. Red mottles and drab mottles and pipes dispersed or in horizons. Carbonate nodules ,3 cm, some with pyrolusite coatings, and rhizoconcretions are dispersed or in bands; carbonate is sparse to common (,20%). Minor dark mottles and Fe/Mn nodules. Local layers of pale silt to very-fine sand, structureless or with ripple cross-lamination and graded beds. Rare gastropods and bivalves, usually below lacustrine layers.	Floodplain deposits, with aggradation of fines and coarser crevasse splays. Variable degree of pedogenesis, including zones of carbonate accumulation and rhizoconcretions.
Lacustrine Deposits	Variable degree of pedogenesis, locally destroying stratification. 1-3 m sheets of .1.3 km extent, and locally within channel bodies. A) Mud sheets: Dark brown stiff clay to yellowish silt, banded to structureless. Minor carbonate as rhizoconcretions, nodules and lenses, local slickensides, roots, red-brown and drab mottles. Efflorescence prominent on weathered surfaces. Sparse gastropods and bivalves. B) Silt/sand sheets: Yellow, laminated and weakly cohesive micaceous silt to very fine sand, grey and red mottles. Carbonate nodules, bands and rhizoconcretions.	Standing-water bodies on floodplains and in abandoned channels.
Channel Fills: Gravel Fills	Up to 5.3 m thick, ribbon to sheet geometry, locally strongly incised fills of reworked carbonate gravel (clasts ,8 cm) with rare bedrock clasts, sandy matrix, poorly lithified to cemented. Silt lenses with rhizoconcretions. Internal erosion surfaces, planar cross-sets (,2.5 m thick) of banded coarse and fine gravel, trough cross-sets, and fining-up cycles of gravel to mud. Bivalves are articulated and disarticulated valves and fragments (single valves commonly in current-stable position); some gastropods.	Plains-fed rivers with gravel reworked from carbonate in floodplain fines. Gravel dunes and downstream accreting foreset bars. Associated with floodplain degradation and gullying.
Sand Fills	Up to 3 m thick. Basal lags of reworked carbonate gravel. Stacked sheets and lenses of fine-medium sand and silt, with mud interbeds. Mainly structureless, with convolute lamination, rare cross-stratification and accretion surfaces. Carbonate cementation prominent, as rhizoconcretions, nodules, calcified tree stumps, and cemented topmost sands. Minor dark (Fe/Mn) nodules.	Plains-fed rivers, associated with floodplain degradation and groundwater cementation. Sands dewatered, possibly through seismic events.
Gully Fills	A) Thickest fills (to 10 m) are incised into floodplain fines, and contain inclined beds that fan out from topmost margin of cut; brown mud, pale silty sand, carbonate gravel lenses. B) Thinner fills (to 3 m) mark extensive degradational surfaces with several meters of relief; redbrown mud and inclined lenses of carbonate gravel; some surfaces carbonate-cemented, or marked by prominent rhizoconcretions.	Floodplain degradation and cutting and filling of ravines, locally linked to incision of main drainages. Colluvial fill from degrading floodplains, and stream flow deposits.
Eolian Deposits	1-2 m sheets with .1.3 km extent, and local lenses within channel bodies. Pale silt to very fine sand, non-cohesive with minimal clay, carbonate-cemented bands, nodules and rhizoconcretions. Low-angled stratification picked out by carbonate cement.	Windblown sand and silt in poorly stratified sheets with local accretion surfaces and growth of vegetation.
Cultural Level	Up to 5 m thick. Layer rich in masonry and pottery, with wells and pits, capping outcrop sections.	Anthropogenic activity, especially prominent on river bluffs.

Table 3 Facies within the Ganga Foreland Basin and their descriptions (Gibling, Tandon, Sinha, & Jain, 2005).

Important features of fluvial sedimentation that are encountered in the study area are point bar deposits and oxbow lakes (Figure 16) that are formed along the course of the Ganga River, due to its meandering pattern. These depositions are characterized by still, reductive conditions and are rich in organic material.

Point bars are sandy deposits of constrained lateral extend, usually lense shaped and often asymmetric. They are typically encountered at the inner part of the curves of a meandering channel. They are usually covered by silt or clay that is rippled, highly bioturbated and contain a high content of organic material (Miall, 1996). Abandoned point bars are encountered in the research area, resulting from the meandering course of the Ganga River.

Oxbow lakes are also very common. They consist of silt and clay and contain a very high organic content. Oxbow lakes develop a swampy environment that is strongly reductive and unaffected by the fluvial dynamics of the river that has previously deposited them (Miall, 1996).

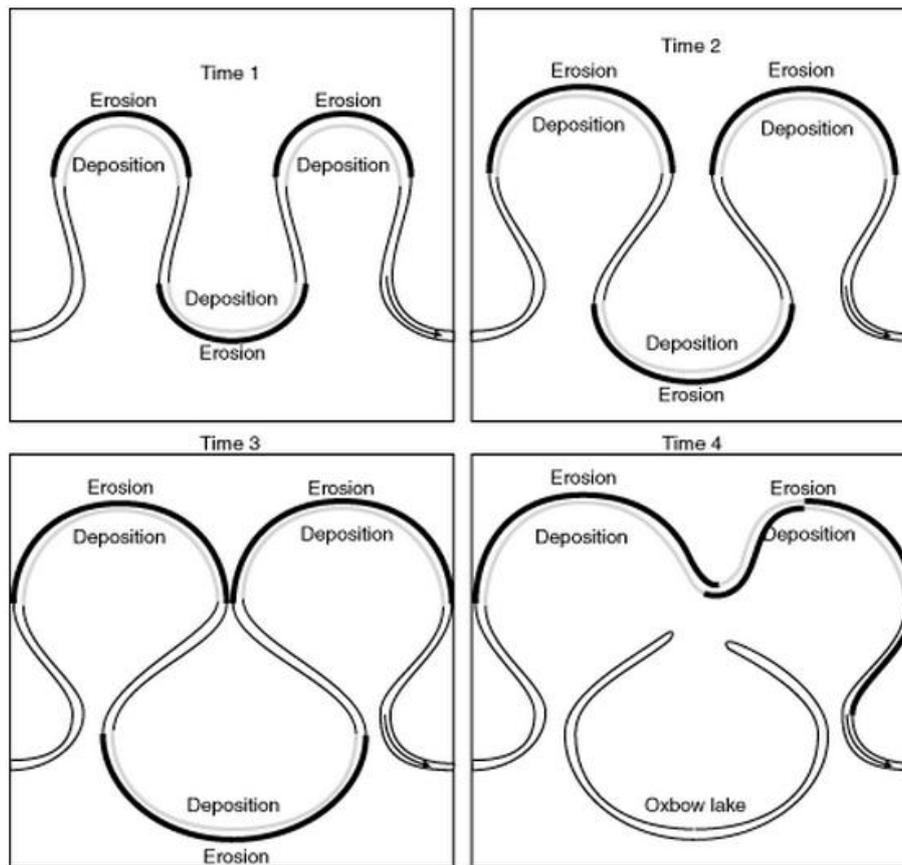


Figure 16 Meandering pattern of a river course and fluvial deposits that are associated with it. The images show the successive development of the channel with time. The external part of the meander loops are eroded (cut banks), while deposition takes place in the internal part, forming point bars. Finally, when the river abandons its course, oxbow lakes, filled with clay and silt are formed, on top of the abandoned sandy channel deposits.

Geomorphology

The Ganga Plains

The most important geomorphic feature of the vast area around Bihar is the Ganga Plains, which covers a large part of it and is drained by a number of tributaries of the Ganga River.

The Ganga Plains occupy a vast area in North Bihar, as well as some tracts to the South. The North Ganga plain forms a continuous stretch in the North, which is fringed by the Siwalik rocks and is merging westwards into Uttar Pradesh and eastwards into the northern part of West Bengal. This plain is drained by the Ghaghra, the Gandak, the Burhi Gandak, the Bagmati, the Kosi, and the Mahananda (Mahadevan, 2002).

The Ganga Plains coincide geographically with the Ganga Drainage Basin (Central Ground Water Board, 2010; Mahadevan, 2002). The Ganga Drainage Basin extends over an area of 1086000 km² and lies in India, Tibet (China), Nepal and Bangladesh. The drainage area lying in India is 861404 km², which is nearly 26.2% of the total geographical area of the country. The sub-basin lies in the States of Uttar Pradesh, Madhya Pradesh, Bihar, Rajasthan, West Bengal, Haryana, Himachal Pradesh and the Union Territory of Delhi. The State-wise distribution of the drainage area is given in Table 4.

State	Drainage area (sq.km)
Uttar Pradesh	294364
Madhya Pradesh	198962
Bihar	143961
Rajasthan	112490
West Bengal	71485
Haryana	34341
Himachal Pradesh	4317
U.T. of Delhi	1484
Total	861404

Table 4 State-wise distribution of the drainage area of the Ganga River (Ministry of Water Resources of India).

The Ganga originates as Bhagirathi from the Gangotri glaciers in the Himalayas at an elevation of about 7010m in Uttarkashi district of Uttar Pradesh and flows for a total length of about 2525 km up to its outfall into the Bay of Bengal through the former main course of Bhagirathi-Hooghly (Central Water Commission, Ministry of Water Resources of India).

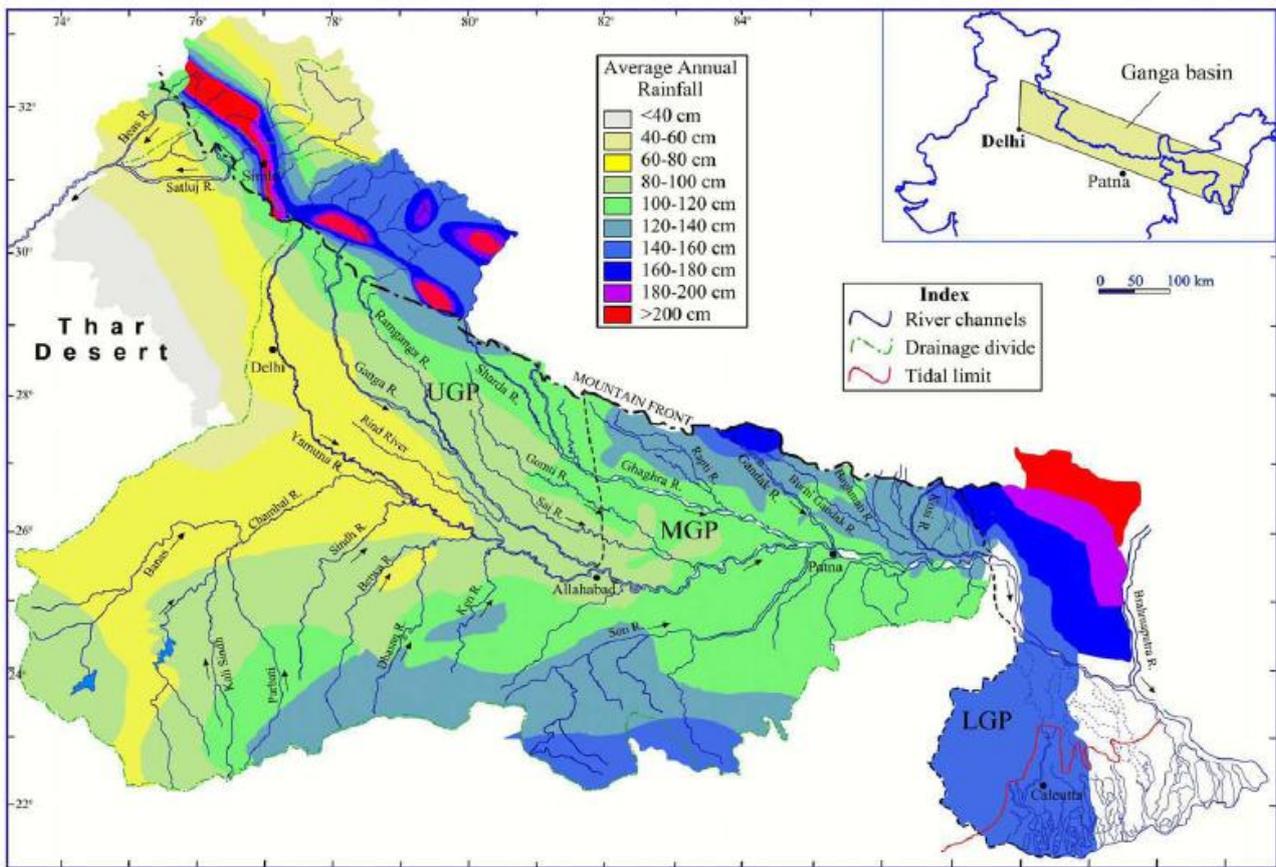


Figure 17 The Ganga Drainage Basin. UGP = Upper Ganga Plain, MGP = Middle Ganga Plain, LGP = Lower Ganga Plain (Sinha & Sarkar, 2009)

The study area belongs geographically to the Middle Ganga Plain that is more extensive in the west than the eastern parts. It is interrupted in Munger by the North-South trending Kharagpur hills. The western part covers the major portions of Patna, Rohtas, Bhojpur, Nalanda, Aurangabad, Gaya and Munger districts. In the eastern part, the alluvium occurs as embayment in the Bhagalpur district, with the Rajmahal hills as the Eastern boundary (Mahadevan, 2002).

Geomorphology of Bihar

Based on broad geomorphology parameters, Bihar can be divided into three geomorphic domains (Figure 18):

- 1) An uplifted block of South Bihar Highlands comprising the Chotanagpur Plateau and the Rohtas and Rajmahal Plateau and their associated uplands
- 2) The transition zone between the South Bihar Highlands and the Great Ganga Plains, constituting the Central Bihar Plains
- 3) The Ganga Foredeep of the North Bihar Plains bounded by the rising Himalaya in the north and the Tarai region in the extreme NW.

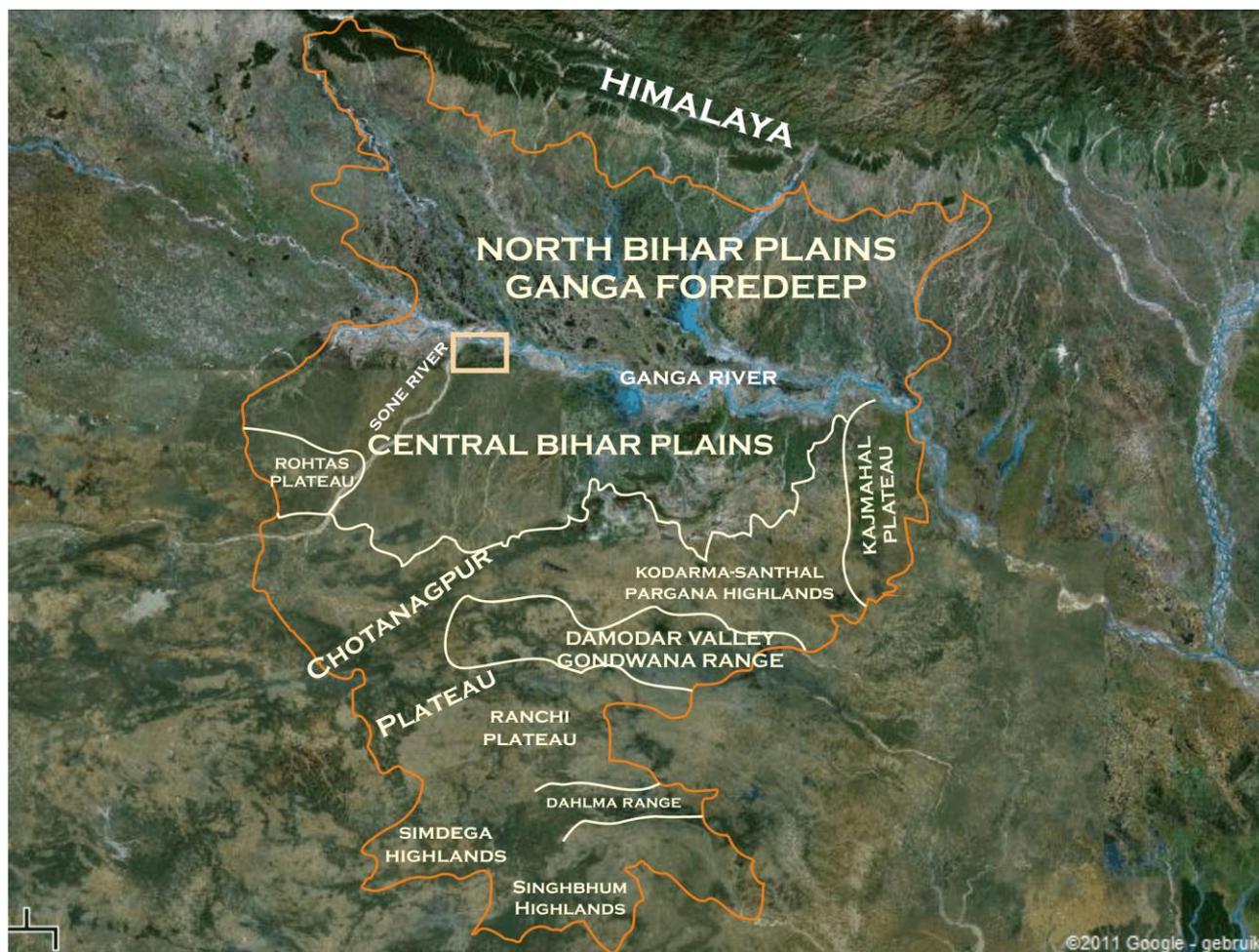


Figure 18 Satellite image indicating the various geomorphic features of Bihar and its neighboring state of Jharkhand, according to Mahadevan, 2002. The research area is also indicated. Image obtained by Google Maps.

The first two geomorphic units comprise the Middle Ganga Plain, in which the study area is included (Central Ground Water Board, 1999). Consequently, a large part of the geological and geomorphological characteristics of Bihar are associated with those of Middle Ganga Plain.

An important geomorphic sub-unit in the Rohtas Plateau acts as a sediment source for Sone River. It comprises of Vidhyan sediments of late Proterozoic age. It rises to an average height of about 500 m. Its northern side is steeply cut by rivers (Mahadevan, 2002).

The state of Bihar can broadly be divided into two physiographic divisions: a) The Chotanagpur plateau region of central and southern Bihar, and b) The Ganga Plains with a fringe of Himalayan

foothills and the Tarai region in the extreme NW. The Ganga River divides the plain into two - the Northern Ganga Plain, known as North Bihar and the Southern Ganga Plain, included in South Bihar (Mahadevan, 2002).

There are three river basins in the state, namely the Ganga, the Subarnarekha and the Brahmani. The Ganga River enters Bihar in the middle region, 115 km downstream from Varanasi. In this region, important tributaries, including Son River, join the Ganga. The Son rises at Sonabhadra at elevation of 600 m in Madhya Pradesh, passes through the Palamu district of Bihar to finally join the Ganga about 16 km upstream of Danapur and just a few km Western to Maner in Patna district (Central Ground Water Board, 2010) .

Hydrogeological characteristics

Bihar has two main rivers, the Ganga and the Sone River. The Ganga has an average depth of 16 m and a maximum depth of 30 m. It shows a fluctuation of about 1 m during the monsoon period (Central Ground Water Board, 1999). The course of the two rivers in respect to the studied area is shown in Figure 17.

The state of Bihar can broadly be divided into two hydrogeological groups. One is characterized by aquifers in fissured formations and one by aquifers in porous formations. Patna district and Maner block are characterized by aquifers in the recent alluvium (Quaternary and Upper tertiary), which are further divided into Newer Alluvium aquifers (Holocene) and Older Alluvium aquifers (Pleistocene). In general, these aquifers are fairly thick and regionally extensive, either confined, or unconfined and they extend vertically to a depth of 300 m (Central Ground Water Board, 1999).

As it is mentioned above, the Ganga River floodplain is underlain by thick Quaternary sediments with the newer Alluvium of Holocene age overlying the Older Alluvium of Pleistocene age. Boreholes along the Ganga generally manifest a thick clay layer on top, followed by fine to medium sand, which locally shows abandoned channel characteristics, rather than appearing in extensive layers. These sandy formations comprise the aquifers of Bihar. The thickness of the clay layer shows a maximum in Patna (90 m) and gradually reduces towards the E and W (Acharryya, 2007; Central Ground Water Board, 2010; Saha, Sahu, & Chandra, 2010). These differences in thickness can be attributed to point bar deposits morphology. The characteristic stratigraphy of Bihar can be seen in the relevant paragraph. Closer to Patna, a confined and laterally restricted sandy aquifer of 5 m thickness approximately is encountered at about 20 m depth (Central Ground Water Board, 1999).

In South Ganga plains and specifically near the Ganga course, the discharge of aquifers up to 250 m depth is approximately 150-250 m³/hour, with a high transmissivity of values ranging from 6000 to 12000 m²/day. These values gradually reduce towards the southern marginal plain (Central Ground Water Board, 2010).

The Central Ground Water Board of India explored the subsurface of Bihar by drilling a number of boreholes and carrying out geophysical logging. This research has revealed that the aquifer material is transported from the Himalayas in the Northern Plains and has been transported and deposited there by the Ganga River. In the Southern Plains, the aquifer material has mostly been transferred by the Sone River and it originates from the Chotanagpur plateau. The area between Buxar and Begusarai, which also includes Patna district within it, shows multi-cyclic sedimentary depositions up to a depth of about 300 m, which results in variations in aquifer characteristics. Saline water was only encountered at a depth of 150 m and at the Eastern edge of the State, near Begusarai (Central Ground Water Board, 2010).

Soil types

The soils of Bihar can be divided to seven orders: Entisols, Inceptisols, Aridisols, Millisols, Alfisols, Ultisols and Histosols (Central Ground Water Board, 1999)

Young alluvial soils, red sandy soils and yellow soils are the major types. In general they have developed upon three different groups of parent materials. The soils of North Bihar have developed upon alluvial depositions transported from relatively younger formations where physical weathering is predominant and the soils developed in them are generally coarser in structure (Central Ground Water Board, 1999).

The soils of South Bihar, north of Chotangapur plateau have been developed mainly from alluvial soils transported from the older formations of Gondwana land, where chemical weathering is dominant. The soils of South Bihar plains are finer in texture and contain higher amounts of clay than silt. The parent materials of Chotangapur have either developed in situ due to decomposition of various rocks and minerals found there, or are materials transported to a comparatively small distance from the place of their origin (Mahadevan, 2002).

The study area is covered by Entisols (Udifluvents - younger alluvial soils) and partly by Inceptisols (Ustochrepts and Haplaquepts - Calcareous alluvial soils) (Central Ground Water Board, 1999) .

Entisols and more precisely younger alluvial soils are confined on either sides of Ganga, which are deficient in nitrogen, phosphoric acid and humus. Texturally they are sandy to loamy sand, pH values being on the alkaline side (Central Ground Water Board, 1999) .

What is arsenic contamination?

Arsenic (As) is a chemical element that can occur in the environment in several oxidation states (3, 0, +3 and +5), but in natural waters is mostly found in inorganic form as oxyanions of trivalent arsenite [As(III)] or pentavalent arsenate [As(V)]. Organic forms of arsenic may occur where the water is significantly impacted by industrial pollution (Smedley & Kinniburgh, 2001). There are various release and mobilization mechanisms for Arsenic in groundwater that have been suggested by researchers worldwide. Arsenic in general does not exist naturally in groundwater. Its occurrence is related to geological weathering mechanisms that may be triggered by a number of conditions, or to human activity (Smedley & Kinniburgh, 2001; IGRAC, 2006) and varies from one geological setting to the other.

National and international standards for maximum concentrations of arsenic in drinking water have been declining since the early 1980s as the high toxicity of arsenic has become apparent (Plant, Kinniburgh, Smedley, Fordyce, & Klinck, 2004) According to World Health Organization guidelines, arsenic concentration in drinking water should not exceed the amount of 10 ppb, in order for the water to be considered as safe for the people who consume it. Following the same guideline, the Bureau of Indian Standards has notified a standard of 10 ppb, while, on the other hand, the Rajiv Ghandi National Drinking Water Mission has set the maximum permissible limit for arsenic concentration in groundwater much higher at 50 ppb (IGRAC, 2006; Nickson, et al., 2007). This limit is also accepted in many countries worldwide, despite the impact this arsenic concentration in drinking water may have on peoples' health.

Arsenic concentration in natural environments varies largely both spatially and temporally, even among closely spaced study areas.



Figure 19 Typical moment from the daily life in the rural areas of Maner.

From large scale to local

Arsenic contamination in drinking water and groundwater has become a major issue that many regions around the world need to deal with during the last decades. There is a large number of countries (Figure 20) that are suffering from arsenic contamination in groundwater (IGRAC, 2006). Details regarding the countries affected by arsenic groundwater contamination and the possible contamination source for each country are included in Appendix A.



Figure 20 Summarized world distribution of documented problems with As in groundwater (> 50 ppb), as reported in 2002. The area of Bihar is not included among the arsenic contamination prone areas (IGRAC, 2006). The lower part of the plot is shifted.

India is included among these countries. The area of Bengal (Bangladesh and West Bengal, India) have repeatedly been reported as highly affected areas, where arsenic levels in groundwater and drinking water are constantly increasing, along with the impacts this has on the local communities (Chakraborti, et al., 2003; Ghosh, 2003; IGRAC, 2006; Seddique, et al., 2008).

Groundwater arsenic contamination in the Lower Ganga Plain of West Bengal, India, was first identified in July 1983. In the combined areas of West Bengal and Bangladesh, around 150 million people have access to sources of arsenic contaminated groundwater only. Although West Bengal's arsenic problem reached public concern almost 20 years ago, and its constant monitoring by researchers shows a gradual increase in arsenic affected population, there are still few concrete plans, much less achievements, to resolve the problem.

Arsenic in groundwater in Bihar was first reported in 2002 in Bhojpur district. Public Health and Engineering Department (PHED), Government of Bihar, initiated the blanket testing of hand pumps and shallow tube wells and reported arsenic in parts of 12 districts on the banks of river Ganga. The hand pumps and shallow tube wells with Arsenic concentration higher than the national permissible limit of 5 ppb and water being unfit for consumption were colored red by PHED. CGWB initiated exploratory drilling and ground water sample analysis and identified another 3 districts with higher concentration in Arsenic. By now, 57 blocks in 15 districts of Bihar, mainly along the river Ganga are affected.

The affected districts within Bihar are: Bhojpur, Buxar, Patna, Saran, Vaishali, Begusarai, Samastipur, Lakhisarai, Purnea, Kathitar, Khagaria, Darbhanga, Bhagalpur, Kishanganj, Munger (Figure 21).

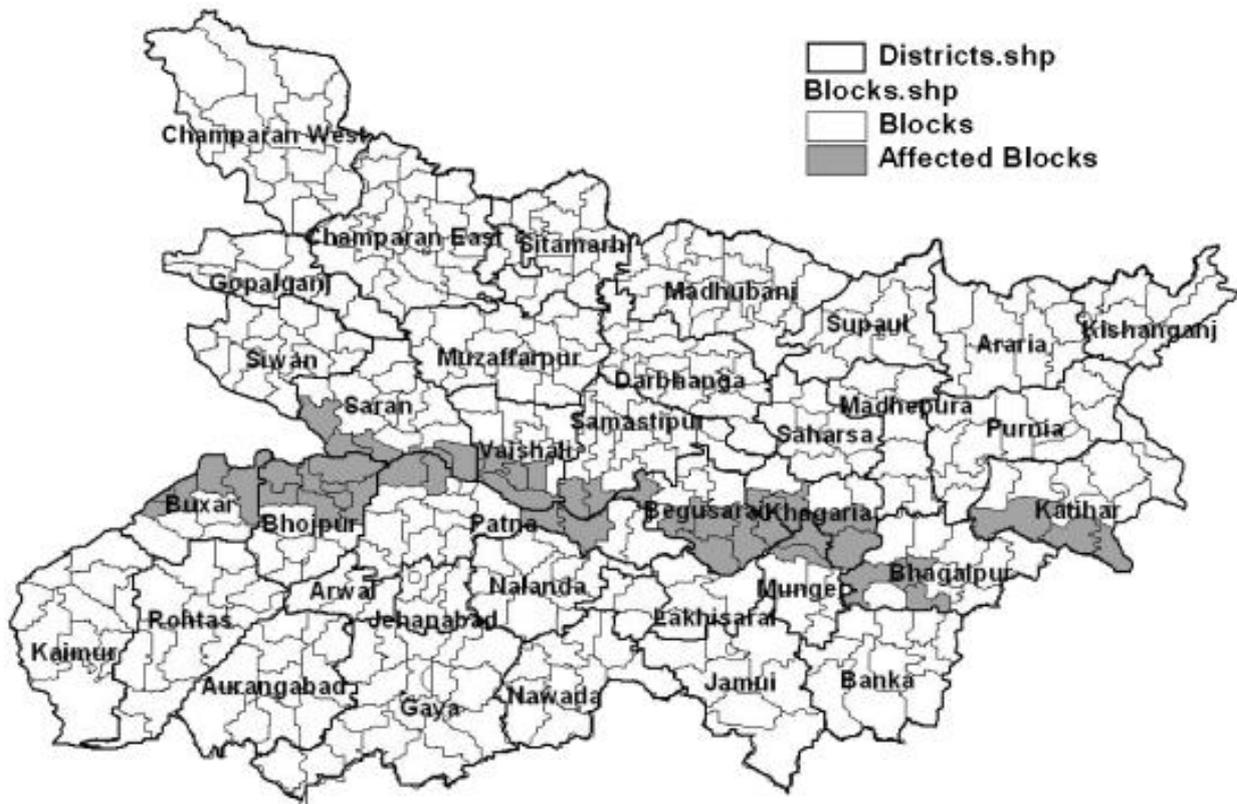


Figure 21 Map of Bihar, showing districts that have been affected by arsenic (Central Ground Water Board, 2010).

Arsenic concentration reported so far, varied from below detection limit to 1810 ppb. Maximum concentration was found in Haldi Chhapra (Maner block), where one of the present survey's boreholes is located. Fluoride measurement data from the same source indicate that Fluoride presence does not coincide with Arsenic presence in the ground water. Iron levels also do not seem to correlate positively with Arsenic levels (Central Ground Water Board, 2010).

In 2005-2006, PHED and A.N. College, Patna, with assistance from UNICEF, conducted testing in 11 districts of the state. This is an ongoing research, which aims to monitor the arsenic levels in the groundwater and the effect it has on local people (Nickson, et al., 2007).

Sources, release and mobilization mechanisms

Arsenic is unique among the heavy metalloids and oxyanion-forming elements (e.g. As, Se, Sb, Mo, V, Cr, U, Re) in its sensitivity to mobilization at the pH values typically found in groundwater (pH 6.5-8.5) and under both oxidizing and reducing conditions (Smedley & Kinniburgh, 2001).

There is little knowledge regarding the rate of solid-phase reduction of arsenic. Experiments on soils and sediments have indicated that some of the arsenic was released before Fe, which implies reductive desorption from Fe, rather than reductive dissolution as a release mechanism (Masscheleyn, De Laune, & Patrick, 1991).

Regarding the sources of arsenic, there are over 200 minerals by which arsenic may be released (Smedley & Kinniburgh, 2001). Approximately 60% of natural arsenic minerals are arsenates, 20% sulfides and sulfosalts, and the remaining 20% are arsenides, arsenites, oxides, alloys, and polymorphs of elemental arsenic (Plant, Kinniburgh, Smedley, Fordyce, & Klinck, 2004). Minerals that primarily contain arsenic in their lattice are presented in Appendix B.

Besides these minerals, arsenic can also be encountered in the crystal structure of rock-forming minerals (pyrite, chalcopyrite, galena and marcasite) by the substitution of As for Fe or Al and in sulphide minerals, as a substitute for sulfur (Plant, Kinniburgh, Smedley, Fordyce, & Klinck, 2004; Smedley & Kinniburgh, 2001). High arsenic concentrations are also found in many oxide minerals and hydrous metal oxides, either as part of the mineral structure or as sorbed species. Concentrations in Fe oxides can also reach high weight percent values. Adsorption of arsenate to hydrous Fe oxides is particularly strong, while adsorption to hydrous Al and Mn oxides may also be important if these oxides are present in quantity. Finally, arsenic may also be sorbed to the edges of clays and on the surface of calcite. Arsenic sorption by minerals is the main reason for low and non-toxic concentrations of arsenic found in most natural waters (Smedley & Kinniburgh, 2001).

As far as the different sedimentary rocks and unconsolidated depositions are concerned, sands and sandstones tend to have the lowest Arsenic concentrations, reflecting the low arsenic concentrations of their dominant minerals, which are quartz and feldspar. Clays, fine sediments and shales, on the other hand, and especially those that are rich in sulfide minerals, organic matter, secondary iron oxides, and phosphates are expected to have high arsenic concentrations (Plant, Kinniburgh, Smedley, Fordyce, & Klinck, 2004). In black shales, these high concentrations are related to their high pyrite content (Smedley & Kinniburgh, 2001). In addition, all iron and manganese -rich sediments show high arsenic content.

Tables presenting details of arsenic in various natural environments are given in Appendix B.

The interaction between minerals and water comprises the key steps towards arsenic release in groundwater. Thorough research on this topic has shown that Arsenic is released by sediments in the groundwater after flooding and anaerobic conditions have occurred. Redox potential (Eh) and pH are the most important factors controlling arsenic speciation in natural waters (Nath, Charabarti, Burnol, Stüben, Chatterjeeb, & Charlet, 2009; Plant, Kinniburgh, Smedley, Fordyce, & Klinck, 2004; Smedley & Kinniburgh, 2001).

From a purely chemical point of view, the two main triggering mechanisms for arsenic release in groundwater (Plant, Kinniburgh, Smedley, Fordyce, & Klinck, 2004; Smedley & Kinniburgh, 2001) are:

- 1) The development of high pH (>8.5) conditions in semi-arid or arid environments usually as a result of the combined effects of mineral weathering and high evaporation rates. This pH change leads either to the desorption of adsorbed As (especially As(V) species) and a range of other anion-forming elements (V, B, F, Mo, Se and U) from mineral oxides, especially Fe oxides, or it prevents them from being adsorbed.

- 2) The development of strongly reducing conditions at near-neutral pH values, leading to the desorption of arsenic from mineral oxides and to the reductive dissolution of Fe and Mn oxides, also leading to As release. Iron (II) and As(III) are relatively abundant in these types of groundwater and SO_4 concentrations are small (typically 1ppm or less). Large concentrations of phosphate, bicarbonate, silicate and possibly organic matter can enhance desorption of arsenic because of competition for adsorption sites.

Regarding arsenic transport in groundwater, there are few observations of arsenic transport in aquifers, and its rate of movement is poorly understood. The transport of arsenic, as that of many other chemicals, is closely related to adsorption-desorption reactions. Arsenate and arsenite have different adsorption isotherms. They, therefore, travel through aquifers at different velocities, and tend to be separated (Smedley & Kinniburgh, 2001)

Various studies indicate a rather low partition coefficient (K_d) or retardation factor of arsenic species. Factors controlling the partition coefficients are also poorly understood, and they involve the chemistry of groundwater, and the surface chemistry and stability of the solid phases (Plant, Kinniburgh, Smedley, Fordyce, & Klinck, 2004).

Health impact

Arsenic is a highly toxic carcinogen (Category I) and also a mutagen or teratogen (harming fetus) (World Health Organization). Arsenic poisoning has mainly been detected through testing samples of tube-well water and human tissues-hair, nail, skin and urine. There is a large number of symptoms that have been reported as arsenic poisoning related by the World Health Organization. The most common ones are caused by Arsenicosis and Bowen's disease and include skin problems (such as color changes on the skin, and hard patches on the palms and soles of the feet), skin cancer, cancer of the bladder, kidney and lung, and diseases of the blood vessels of the legs and feet, and possibly also diabetes, high blood pressure and reproductive disorders. They are all caused by long term exposure to arsenic contamination (IGRAC, 2006).

Arsenic poisoning symptoms (Figure 22) were reported in Maner for the first time less than a decade ago. While on fieldwork related to arsenic drinking water contamination, Dr. A. Ghosh and Dr. N. Bose observed that an important percentage of the population is suffering from itching all over their skin, and also from digestion problems, while a number of people have their skin covered by spots in a large extend. Skin lesions, discoloration of skin, nodules over thickened soles and, in some cases, all over the body were also common. Those initial symptoms bear stark resemblance to the pictures of bodily symptoms obtained from arsenic affected areas of Bangladesh and West Bengal (Ghosh, 2003). While being on fieldwork in the area of Maner, some of these symptoms were also observed on the local people.

Health impact incidents related to arsenic poisoning are not restricted within Patna district, thought. During their research in Bhojpur district, Bihar, (Chakraborti, et al., 2003) reported 60 people with skin lesions, while 57.6% of hair samples and 76.3% of nail samples were found to be above the normal range in terms of arsenic content. Correlation of drinking water arsenic with the concentration in the hair and the nails was positive and similar to their findings in their previous West Bengal and Bangladesh studies.

Besides the blocks that are indicate in Figure 21, the majority of the districts in North Bihar, between the Ganga floodplain and the borders with Nepal, have been reported as affected by arsenic. The map contains a few inconsistencies (Nickson, et al., 2007)



Figure 22 The effect of Arsenicosis on human palms and feet.

Arsenic, stratigraphy and geochemistry

Knowledge is the basis for successful research and the source of solutions to many issues. This paragraph presents suggested source, release and mobilization mechanisms by researchers worldwide, in regimes that are similar to the study area of Maner. West Bengal and Bangladesh will be thoroughly presented, since some correlation with Middle Ganga Plain and Bihar, as far as arsenic contamination triggering mechanisms are concerned, may exist. An insight will be given into the different geological settings and the possible effect they may have on the mechanisms controlling arsenic mobilization. These previous study cases strongly indicate the importance of stratigraphy in the arsenic groundwater issue, as well as attract attention to other key factors.

Previous research

By observing the arsenic distribution globally, one can immediately derive that despite the geochemical and hydro geological differences among the affected areas, there is one major similarity, with respect to the geological setting. The majority of the arsenic affected groundwater can be found in young unconsolidated sediments, usually of Quaternary and often of Holocene age (12,000 years) (IGRAC, 2006). The affected aquifers tend to be in inland closed basins in arid or semi-arid settings, or large alluvial and deltaic plains (Smedley & Kinniburgh, 2001).

A popular theory regarding possible arsenic sources involves pyrite (FeS_2), which besides being an ore mineral, is also formed in low-temperature sedimentary environments under reducing conditions. During its formation, it is likely that some of the soluble arsenic will also be incorporated. Pyrite is not stable in aerobic systems and oxidizes to Fe oxides with the release of large amounts of SO_4 (Smedley & Kinniburgh, 2001). Experimental research by Saha et al., during 2009-2010 in West Bengal has shown that arsenic is derived from the oxidation of arsenic rich pyrite. This mechanism is likely to give arsenate species. In such environments, when arsenite species are found dominating, this may be because of microbial reduction of arsenate to arsenite.

After thorough field and laboratory research in a Holocene aquifer in Bangladesh, (Seddique, et al., 2008) concluded that Arsenic is adsorbed onto mineral particles including Fe and/or Mn oxyhydroxides/ oxides after release from biotite [$\text{K}(\text{Mg},\text{Fe})_2(\text{Al},\text{Fe})\text{Si}_3\text{O}_{10}(\text{OH},\text{F})_2$], when it undergoes chemical weathering. The extent of arsenic mobilization is controlled by the quantity and biodegradability of organic matter, which causes release of arsenic adsorbed onto Fe or Mn oxyhydroxides and oxides in reducing conditions.

Both mechanisms are also associated with a lowering of the groundwater level due to excessive pumping rates.

Combined research by (Hasan, et al., 2007) in shallow aquifers in Bangladesh indicates that the concentration of dissolved Fe in groundwater may be controlled by the precipitation of siderite (FeCO_3), and vivianite [$\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$], and concentration of dissolved Mn by the precipitation of rhodochrosite (MnCO_3). In addition, the presence of organic matter in the sediment, as indicated by concentrations of DOC and HCO_3^- in the groundwater, seems to play a significant role in redox reactions. Groundwater with high Mn relative to Fe shows significantly low levels of arsenic. On the other hand, samples with high dissolved Fe relative to Mn have elevated levels of arsenic. It was therefore suggested that at sites where Mn(IV)-minerals are present in solid phase, the Mn(IV) redox buffering step acts as an important constraint in the terminal electron accepting processes in the aquifers that regulates the mechanism of reductive dissolution of Fe and consequent release of arsenic in groundwater (Hasan, Bhattacharya, Sracek, Ahmed, Broemssen, & Jacks, 2009) The same theory and especially the fact the Arsenic release is active where Fe

concentrations are locally controlled by siderite was also supported by (Nath, Charaborti, Burnol, Stüben, Chatterjeeb, & Charlet, 2009).

In Bhojpur district of Bihar, the geochemical evolution of groundwater indicates that dissolution of detrital calcite and dolomite and infiltration of rainwater are the major processes shaping the groundwater chemistry in the newer alluvium. This process is believed to be responsible for arsenic and iron release in the groundwater. Rainfall infiltration, carrying organic matter from recently accumulated biomass from this flood-prone belt, plays a critical role in releasing arsenic and iron present in the sediment (Saha, Sarangam, Dwivedi, & Bhartariya, 2009).

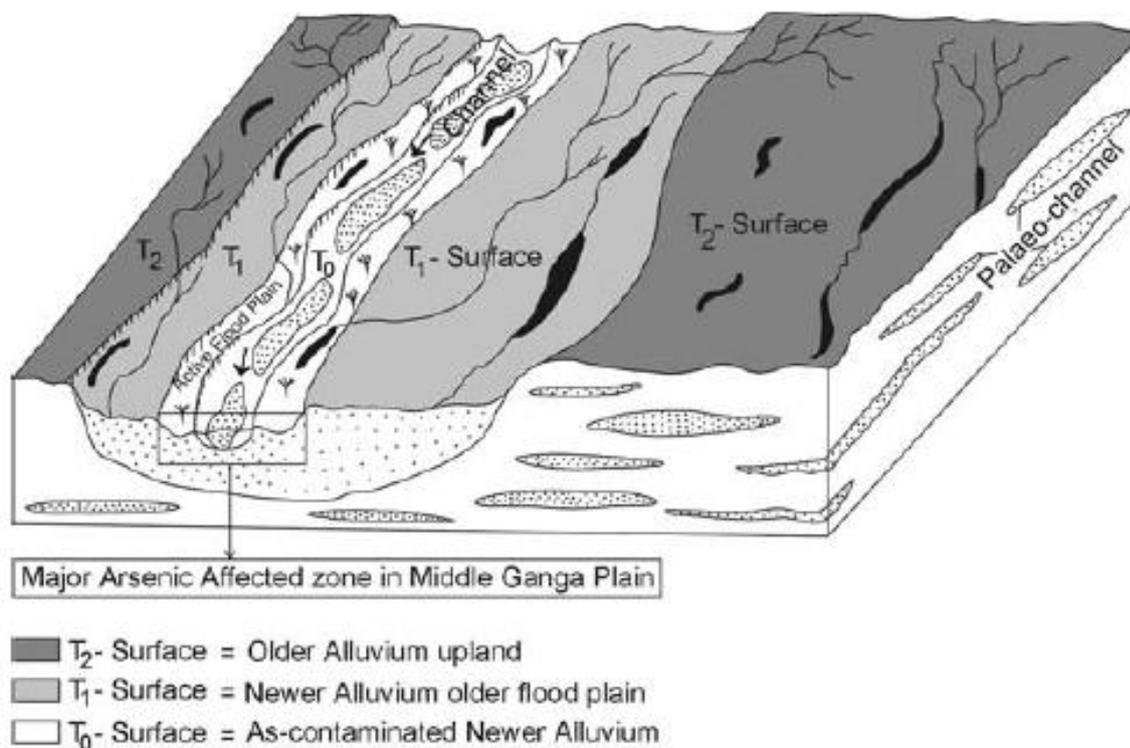


Figure 23 Cross section of the river Ganga bank, indicating alluvial formations that are arsenic affected, in the area of the Middle Ganga Plain (Shah, 2008).

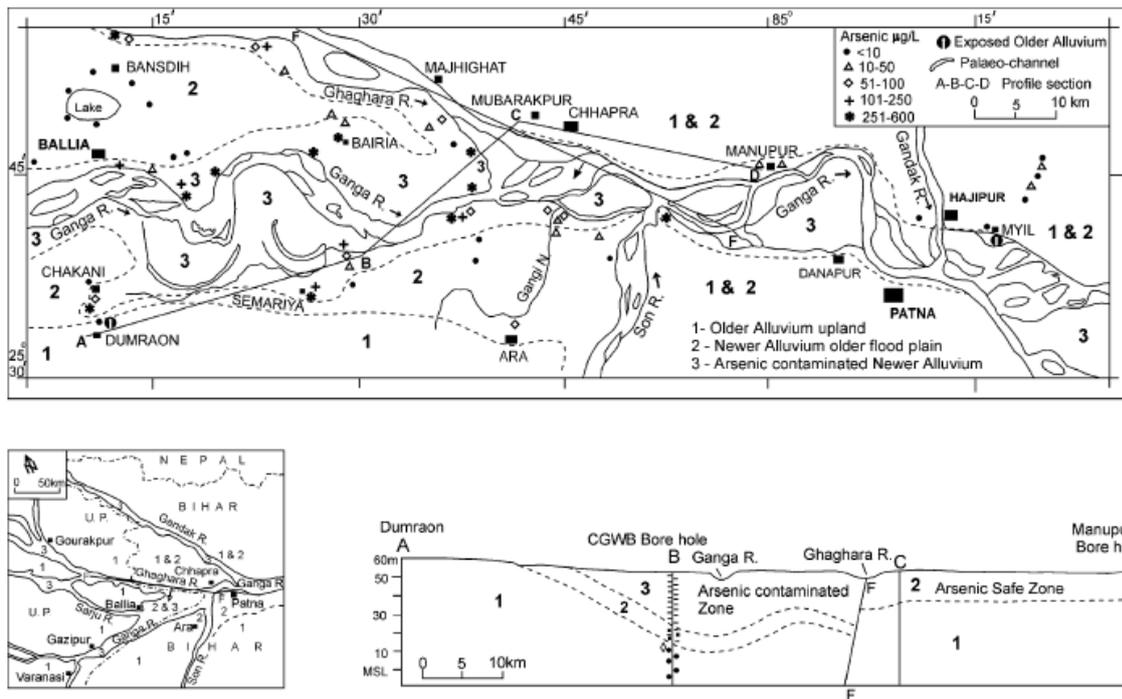
Regarding hydrogeological parameters, the hydraulic conductivity of the different sediments is a key factor in arsenic mobilization (Dowling, Poreda, Basu, & Peters, 2002).

Researchers have also proposed various theories that may explain the sporadic occurrence of high arsenic concentrations in groundwater in the state of Bihar. Some of them agree with the global observations regarding arsenic affected areas. These findings place Bihar among the areas that follow the suggestion that the Quaternary sediments are the source of arsenic contamination in the groundwater.

(Chakraborti, et al., 2003) suggest that according to the fact that most of the arsenic contaminated tube wells are in the depth range of 20-55 m, arsenic occurrence in Bhojpur district may be confined to the Holocene deposits. Their research suggests that the meandering pattern of the river is responsible for the localized depositions of arsenic rich sediment in selected areas along the course of the river Ganga.

Proceeding further into detail, (Acharryya, 2005; Shah, 2008) discovered that arsenic contaminated aquifers are pervasive within narrow entrenched channels and flood plains (T0-Surface) of fine grained gray to black colored argillaceous organic rich Holocene sediments (Newer Alluvium). Contaminated aquifers are often located close to abandoned or existing channels and swamps, since these sediments were poorly flushed by groundwater due to their

low permeability under a high-stand setting (Figure 23). Therefore any arsenic that was released by them, accumulated in groundwater (Acharryya & Shah, 2007) The Pleistocene Older Alluvium upland terraces (T2-Surface) made up of oxidized yellowish brown sediments with calcareous and ferruginous concretions and the aquifers within it are free of arsenic contamination and well flushed by groundwater flow. In addition, these sediments are weakly oxidized in nature and associated groundwater is mildly reducing in general with low iron concentration, and thus incapable to release arsenic (Acharryya, 2005; Saha, Sarangam, Dwivedi, & Bhartariya, 2009).



g. 4. Geomorphological and morphostratigraphic map of Middle Ganga Plain (Ballia-Patna Sector). Symbols in bore-hole column: lay-silt, \bullet - sand, \blacksquare -sand-gravel, \diamond - calcareous concretions. Sand and clay in Older Alluvium, especially in its up section are oxidized yellow-brown colour.

Figure 24 Middle Ganga Plain. Alluvial deposition zones and their relation to arsenic concentration in groundwater and sediment (Acharryya & Shah, 2007).

Hypothesis for Bihar

The versatile nature of Arsenic behavior calls for a need to adopt a model regarding its behavior before organizing the proceeding of this research. After thorough literature study, the following hypothesis was chosen, as a possible mechanism for arsenic groundwater contamination in Bihar.

The hypothesis for Bihar and especially for the geological and hydrogeological setting of Maner block can be summarized as follows:

- 1) Arsenic contaminated groundwater is confined within the shallow sedimentary depositions of Holocene age and is rarely present in the Pleistocene sediments.
- 2) High arsenic concentrations in groundwater are common near wetlands, lakes, floodplain deposits and entrenched channels in the abandoned meandering route of the Ganga. During this research, it will be investigated whether specific sedimentary features of the Ganga River are arsenic bearing, while others are not.
- 3) Arsenic is formed within unoxidized formations and then released to groundwater, due to groundwater flow through the formations.
- 4) There is little indication that sediments deposited by Sone River are actually arsenic affected. This means that the source of arsenic is probably sedimentation of the Ganga River only.
- 5) Arsenic bearing minerals may be present and they will have been transported by the Ganga River from the Himalayan hinterland. The nature of the parent rock is important in order to understand the mineralogical composition and geochemical characteristics of the sediments. While the Himalayan derived sediments appear to be strongly affected by arsenic, the once transferred from the inland, seem to be arsenic free.
- 6) Mica minerals, especially ferrous biotite or iron-coated clay minerals and quartz are expected to be the main sources of arsenic in the groundwater.
- 7) Arsenic is sorbed on Fe or Mn oxyhydroxides and is released under reductive conditions, when enough organic carbon (bacterial microorganisms) is present to complete reductive dissolution of the oxyhydroxides.
- 8) The process of deposition in sediments and following release of arsenic in groundwater needs cycles of fluctuation in water level. Human impact due to over extraction or organic matter input via sewage systems has been proved to add very little to the contamination.
- 9) The flux of arsenic in aqueous phase in the groundwater depends on the hydraulic conductivity of the sediment layers. Geo-hydraulic parameters of the sediments control the amount of arsenic that can be released from the sediment into the groundwater.

Fieldwork

Fieldwork took place in Patna district, Maner block. The aim of the fieldwork was to drill three boreholes forming a triangle in order to investigate the stratigraphy of Maner. The drilling locations (Figure 25) were chosen accordingly and fixed where necessary for drinking water supply was urgent. A detailed workflow schedule and a daily diary of the fieldwork are included in Appendices I and J.

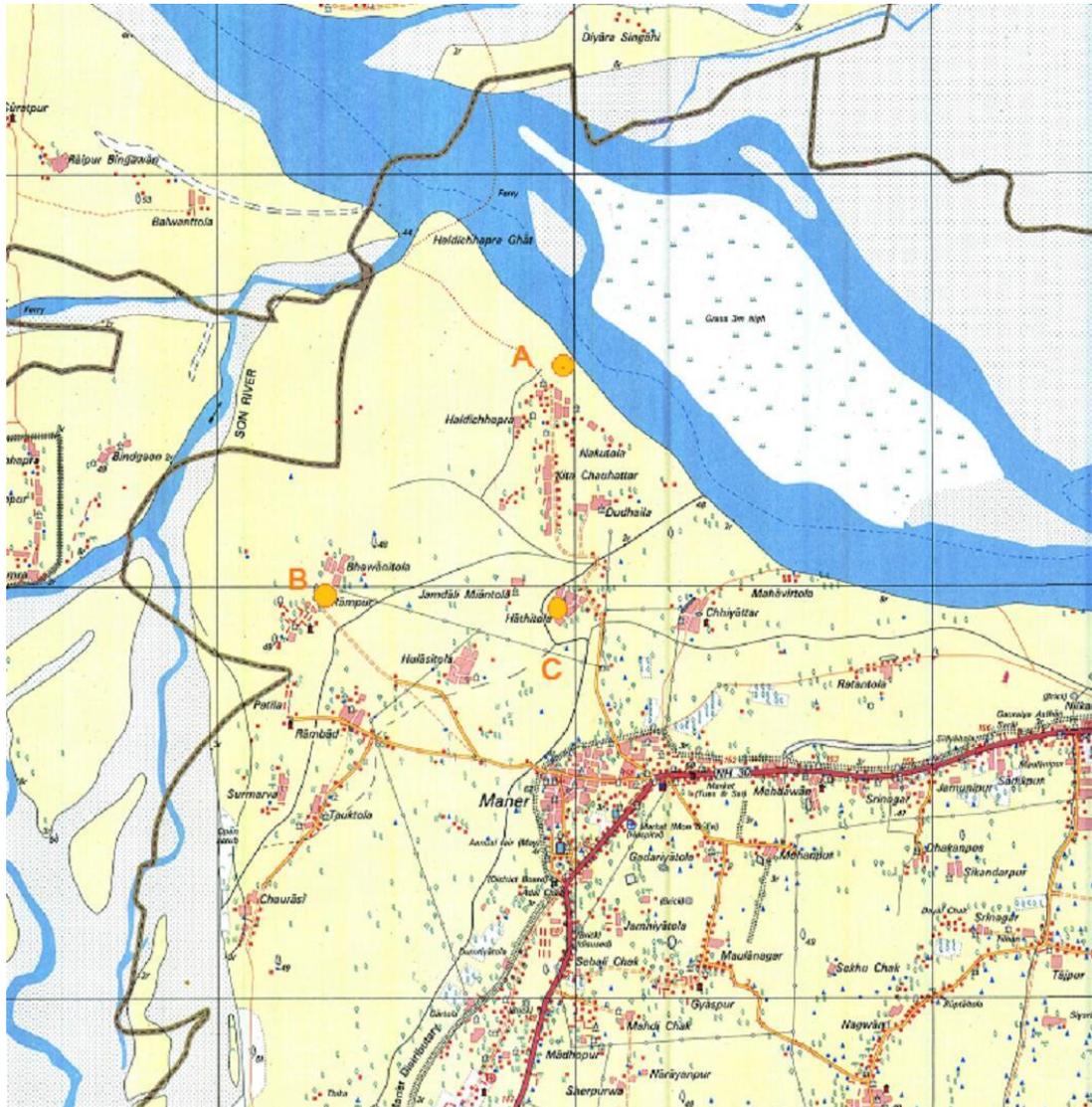


Figure 25 Topographic map of Maner block, indicating the three borehole locations (indicated as points A, B and C).

The borehole locations were originally chosen according to the fluvial depositional pattern of the Ganga and Sone Rivers. The aim was to reach the abandoned channel deposits of the Sone River and to study also other sedimentary features of the Ganga (point bars and oxbow lakes). Satellite images from Google Earth were used in order to detect zones of point bar deposits within the abandoned floodplain of the two rivers. Due to various social and financial reasons though, the boreholes were finally located in areas where the necessity for water supply for the community was high and where permission could be granted by the land owner.

Although mechanical percussive drilling techniques and obtaining undisturbed samples would be more appropriate for the research purpose, due to financial reasons hand sludging was applied, which lead to a generally challenging and experimental way of boring rates and sampling, until the optimum methodologies would be determined.

The technique of sludging was originally developed in ancient India. Bihar is famous for decades now for its expertise in hand sludging, or as it is regionally called, bamboo boring. Some researchers have suggested it as a financially affordable, fast and effective method of boring in order to reach even the deep aquifer layers (Ball & Danert, 1999). Since water management is a measure that needs to be urgently implemented, both for irrigation purposes, and for drinking water, even official sources have suggested bamboo boring as the best available method for deep aquifer exploitation (Central Ground Water Board, 2010). Obtaining data for bore logging by applying this drilling method though, is a pure challenge to a researcher's innovative skills, patience and flexibility.

Drilling procedure and equipment

The boring equipment consists of simple materials, namely the following:

- Bamboo construction (pivot and lever)
- Ropes made of coconut hair
- Steel pipes of varying length and diameter, according to standard drilling specifications (Table 5).

Pipe code	Number of pipes	Length (ft)	Diameter (inches)
A1	1	5	4
A2	1	8	4
A3	1	9	4
A4	6	10	4
B1	1	4.3	2
B2	1	6.9	2
B3	1	12	2
B4	8	Varying around 20 feet	2

Table 5 Length and characteristics of the pipes that were used while drilling.

- Lubricant: Cow dung mixed with water
- Stabilizer: Bentonite-rich soil mixed with water



Before the procedure starts all pipes were measured and their length was noted with permanent marker on them, in order to monitor the drilling depth while boring.

First of all, the bamboo construction is set. This construction consists of a bamboo pivot and a bamboo lever, which enable boring.

The procedure starts by excavating a small pit of one or two feet depth around the boring point.

The pit is then filled with water and lubricant. It works as the borehole water supply. The first feet are manually bored by the driller. Then an 8 feet long pipe (A2) is tied with the rope on the lever and the boring procedure starts. Percussive boring is carried out by lifting and dropping the pipe. The weight of the pipe, enhanced by the lever, is utilized in order to proceed in depth. When time comes to clean the pipes by flushing the soil core out of them, the weight of one of the drillers on the lever helps to enhance boring.

A bamboo beam is used at the top of the borehole to prevent the pipe from diverging from the hole while boring and to control the water force in the hole, so as to prevent erosion of the walls.





Figure 26 Picture that illustrates the different parts of the bamboo boring structure.

The procedure continues by attaching a 5 feet long pipe (A1) to the 8 feet pipe (A2). After the first 13 feet are completed, the first pipe is substituted by a 10 feet long one (A4). A procedure of alternating 5 feet-10 feet long pipes (A1-A4) is repeated until 76 feet depth is reached. The 5 feet piece (A1) is used alternately at the surface to enable the driller hand sludging to remain comfortably on the ground, squatting as the pipe is being driven into the ground. During boring, lubricant is flowing in the borehole from the water supply pit. This water is circulating through the boring pipe and is flushed again out by the pipe's upper open end. The lubricant it contains, contributes in pushing the soil out of the pipe, along with the water. If the soil has high clay content, then its cohesion is also high and relatively continuous and undisturbed core is obtained as a sample. When the soil is sandy and consequently cohesionless, the sample is obtained as slur, flushed out and washed by the water. The fine particles are not possible to obtain, since they become solute in water.

After the completion of the first 76 feet, the 4" pipes are withdrawn and substituted by 2" pipes. Boring procedure continues by continuously alternating the 2" diameter pipes (B1 to B4) until the depth of 160 feet is reached. At that point, the borehole is completed.

On completion of the drilling, the driller logs the depth of the borehole and commences the cleaning process. The hole is washed by pouring clean water through the pipe into the hole and displacing the mucky drilling water. With clean water in the hole, the pipe is removed and the screen and casing are inserted. Subsequently, more clean water is poured down into the casing and screen and flows up the annulus, further washing fines and dirty water away from the screen. A head pan of sand removed from the hole during the drilling and washed clear of fines is used as a gravel pack and washed down the borehole annulus.

All casing and screens observed are low cost solutions. The cheapest version is a fabric covered bamboo based screen. The structure is constructed from between 7 and 9 split bamboo slats 10 to 20mm wide and 5mm thick. They are formed on to 20mm long “doughnuts” of cut bamboo. The open latticed structure is tied with string or wire. A cloth covering of either white mosquito netting or synthetic cloth is wrapped around the structure at least twice. This screen is manufactured on site by the drilling workers and is included in the quoted drilling cost. The bamboo is obtained from the fieldwork area. Such screen is estimated to last three years.

Finally, 5" permanent pipes are placed in the borehole. A hand pump (Figure 27) is installed that will then be used to provide the community with drinking water.



Figure 27 Handpump that was installed in a primary school in Hathitola.

Ergonomics and power requirements

As mentioned above, the lever operator raised and lowered the lever with his hands (Figure 28). When drilling, the operator regularly changed the position of his hands and height of his arms in order to remain comfortable. The valve operator starts off standing at the drill pipe and bends over as the pipe penetrates the ground until he ultimately ends up squatting.

The lever mechanical advantage when cleaning is approximately 3:1. Thus the lever operator must exert a force of 108N to lift 30 ft of water filled pipe length. During the cleaning process, the mean stroke rate was 0.8 strokes/second, with a stroke length of approximately 1 m. Thus the operator is working at a rate of approximately 86 watts. This is just above 70W, which is considered to be a comfortable rate for an adult to work at continuously.

The lever mechanical advantage varies from approximately 2:1 to 3:1. Taking a ratio of 2:1, the lever operator must exert a force of 160N to lift 10m water filled pipe length. The stroke length varied from 20 to 50cm with a mean stroke rate of 1.8 strokes/second. Assuming a stroke length of 0.4m, and mechanical advantage of 2:1, the lever operator must work at a rate of approximately 120W for a 10m-pipe length (Ball & Danert, 1999).

The drilling rate varied, due to the fact that drilling was regularly paused to give adequate time for core description and logging and to obtain and seal the samples for laboratory testing.



Figure 28 The weight of one man was being used in order to flush the sediment sample out of the boring tube, when large depths were reached.

Sampling



Figure 29 Example of clay core sample, as obtained while drilling.

The applied boring procedure dictates that boring takes place for 5 feet and then the pipe is washed out by water that circulates in it, in order to obtain the soil sample. After the sample was obtained, it was registered in a specially designed log paper. When necessary, samples were taken for laboratory testing, in sealed plastic bags.

As mentioned above, while drilling through the clay layers, undisturbed and almost continuous core (Figure 29) was obtained, which would then be laid on a plastic sheet and examined thoroughly for sedimentary structures, fossils etc.

While penetrating sand or gravel layers, though, their lack of cohesion resulted in their coming out of the pipe in a slurry form, flushed by the circulating water. This means that all the sandy and gravelly samples obtained during drilling are disturbed. Sedimentary structures could not be registered in the log. At first, these samples were obtained by filling a bucket (Figure 30) with the slurr that was coming out of the pipe and then filtering it through a very fine piece of cloth. This was then proven to be both time consuming and unsuccessful, because the different grain sizes from different layers would be mixed and impossible to distinguish. As a result, sand and gravel samples were obtained by filling one bucket for each new layer that was encountered while drilling. Every time the drilling would pause for the pipe to be washed, a successive sequence of buckets would be filled and the samples would be examined. Then, stratigraphy was registered in log paper, along with a description of grain size, color and mineralogy. Examples of bore logs are given in the following chapters.

It was originally planned to collect one water sample for each soil sample obtained, in order to correlate arsenic concentration in the different layers with arsenic concentration in the water contained in them. This would give a spatial distribution along the stratigraphic column. The drilling technique that was followed, though, could not allow this, since water flowing out of the borehole while drilling was mixed with lubricant. It was therefore decided that only one water sample would be obtained by the aquifer, after the hand pump would be installed and operated for a short period of time. These water samples were then tested for arsenic concentrations. A detailed registry of the samples that were obtained while drilling is included in Appendix C, while pictures of the samples are presented in Appendix L.



Figure 30 Examples of how samples were obtained and filtered during the drilling procedure.

Hand pump arsenic levels database

Arsenic levels were previously measured and monitored by Dr. Ashok Ghosh and Team Arsenic of A.N.College, Patna in. When this research was carried out, no GPS equipment was available. As a result, the well and hand pump locations were registered by the owner's name. This registry was updated by obtaining GPS measurements for the hand pumps that are located within the research area and by determining the depth after interviewing the owners.

A database with the village name, the location coordinates, the hand pump depth and arsenic concentration was built. This database is included in Appendix D. The idea for this research was that the data would then be used as an input in the 3D model to indicate the location of aquifers and their level of contamination by arsenic. Since only three boreholes could be drilled and as a consequence, the lateral extend of the aquifers could not be determined with accuracy, these measurements could contribute in making the model more detailed and give an idea of the aquifers' dimensions. Besides, as it was mentioned above, vertical distribution of arsenic levels along the depth of each borehole could not be achieved. These data can also provide with an idea of the different arsenic levels in different depths and aquifers, since hand pumps are installed in various depths.

The spatial distribution of arsenic in drinking water can be seen in Figure 31. Hotspots of arsenic concentrations above 50 ppb are mostly located near the Ganga River. The results indicate that 18% of the handpumps are arsenic free, 25% are arsenic affected, but below the acceptable limit of 50 ppb, while 56% can be characterized as arsenic contaminated (> 50 ppb), with concentrations that often exceed 100 or 200 ppb.

These arsenic hotspots in the groundwater are aligned in a NE-SW direction (Fig. 31).



Figure 31 Distribution of arsenic in drinking water of the handpumps that are located within the research area (Maner block). The image is obtained by Google Maps.

Arsenic Removal System installation

After installation of the hand pumps, it has been planned by Team Arsenic and A.N.College to install Arsenic Removal Systems in the three locations where the hand pumps were placed. Due to lack of time and insufficient funds, they could not be directly installed.

The Removal System that was chosen for this purpose is ArsenX^{NP} (Sarkar, Blanley, Gupta, Ghosh, & Gupta, 2007). It has already been installed and successfully operating in many villages in West Bengal.

The principles for Arsenic removal in ArsenX^{NP} are based on anion exchange after allowing oxidation of ferrous iron and subsequent precipitation of HFO particles. This method is fully in accordance with the suggested mechanism of Acharyya (2005) and Shah (2007) for arsenic release and mobilization mechanisms in Bihar. Activated alumina is used as an absorbent medium. Details regarding the functionality and related mechanisms are included in (Sarkar, Blanley, Gupta, Ghosh, & Gupta, 2007).

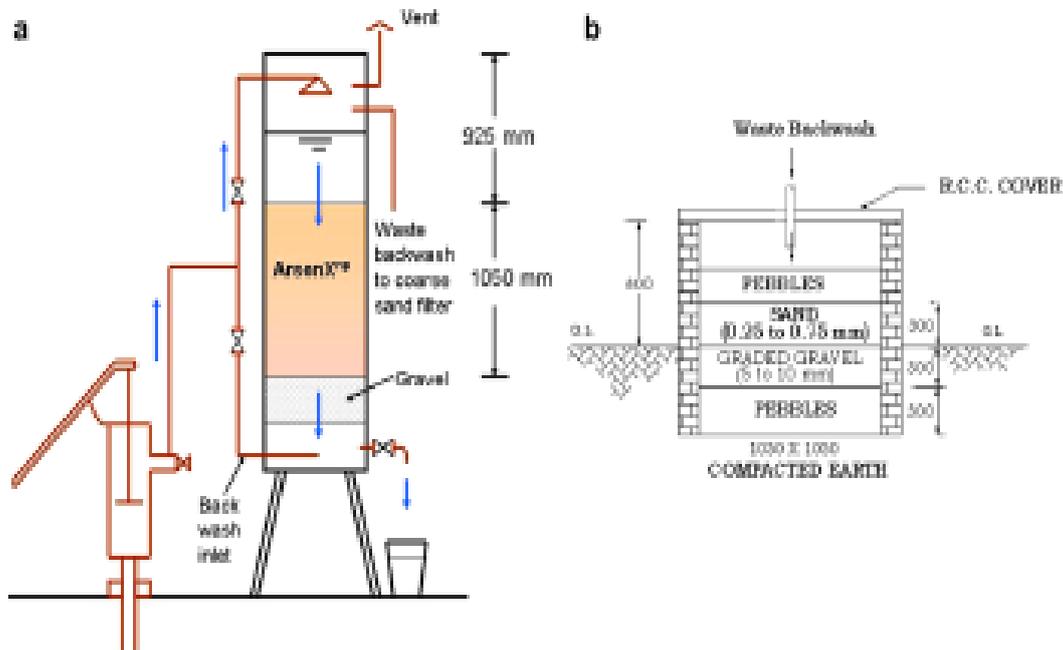


Figure 32 The design of ArsenX arsenic removal system (Sarkar, Blanley, Gupta, Ghosh, & Gupta, 2007).

ArsenX^{NP} consists of an adsorption column (diameter 35 cm, height 2 m), which is a gravity-fed system operating in down flow mode. Apart from the adsorption column, there is a coarse-sand filter to contain the backwash waste water from the column, which contains arsenic-laden precipitates of ferric hydroxide or hydrated ferric oxide (HFO). The arsenic removal unit will be installed at the top of the well, attached to the hand pump (Figure 32).

Interviews, discussions and obtaining data

Before my departure for India, part of my stay there was planned to include an assessment of social aspects regarding the Arsenic contamination issue. Unfortunately, this was not possible, due to time pressure. Fieldwork needed to be completed successfully and our visits to Maner took more time than originally estimated. In spite of this, some interesting interviews with researchers on the field of Arsenic contamination and with geologists and geohydrologists were arranged, which provided with valuable information regarding the geology of the research area and the arsenic issue in Bihar and Maner. Interesting ideas were put forward and their suggestions were of great help in the project's procedure.

It was interesting to see that Bihar is indeed a place where little research has been carried out on the arsenic issue, contrary to West Bengal and Bangladesh. The rising necessity for it though, has resulted in the beginning at a brave effort towards this direction.

One problem that should be stated here is the lack of communication and cooperation among the different research teams. This limitation in data exchange has important consequences, one being the deterioration of an otherwise very detailed and accurate research, since results cannot be cross-correlated.

I faced this reluctance to share data myself, after trying to obtain detailed geophysical data from a borehole drilled by the Central Ground Water Board in the area of Maner. Although all my meetings with the people there were welcome and my discussions with them were fruitful in outcome, they were obviously skeptical about sharing these data with me. The result is that instead of a 3D model based on data from four boreholes; this research will need to be limited to data implementation from the three boreholes that were drilled during fieldwork.

Parts of these discussions are already included in previous chapters as scientific reference in the respective issues.

Data processing and results implementation

Due to the unexpected elections in Bihar, fieldwork and laboratory analysis needed to be carried out as fast as possible and to be concluded three weeks earlier than originally planned. Data implementation was further carried on in India, while a major part of it was concluded in TU Delft.

Data implementation includes the following steps:

- a) Design of the bore logs in Corel Draw X4 and X5.
- b) Provide with an indication of the continuity and lateral extend of the layers and the structure of the subsurface.
- c) Laboratory analysis of the samples (X-Ray Diffraction, Scanning Electron Microscopy and Arsenic content estimation by applying Ultra Violet Photospectrometry)
- d) Implementing the laboratory and fieldwork results in terms of the hypothesis that was previously stated for Bihar regarding arsenic contamination in groundwater.

It was initially planned to build a 3D geotechnical model in PETREL. This was not possible, given the fact that the drilling method and data acquisition on field cannot provide with accurate geotechnical data and information of the local Quaternary stratigraphy. Alternatively, this research focused on more data acquisition by carrying laboratory testing on the different layers and units in order to determine the source of Arsenic release and the mobilization mechanism, with respect to mineralogical characteristics and sedimentary facies of the different layers.

Borehole data

Borehole data, namely each layers characteristics and sedimentary structures, as described on the field were first registered in special log paper and then designed by using Corel Draw version X4 and X5 for visualization purposes. Some examples are given below, while more detailed borehole data, as obtained and registered on field, are included in Appendices E, F and G. On the right side of the borelogs, observations regarding the grain size, mineralogical composition and Arsenic concentration were added during a later stage of the data implementation.

Data extrapolation

Due to the drilling methodology that was applied, the data obtained during fieldwork were not continuous. As a result, core logging was only possible when clayey material was encountered. Clayey layers were obtained in pieces of an average length of 6 inches each (approximately 15.2 cm). Sandy layers were obtained in slurry form. Consequently, it was not possible to estimate the exact layer thickness, to describe sedimentation features within the sand layers and to determine whether the grain size of a sedimentary unit increases upwards or downwards.

At first, samples were registered in a discontinuous form, as it is demonstrated in Figure 33.

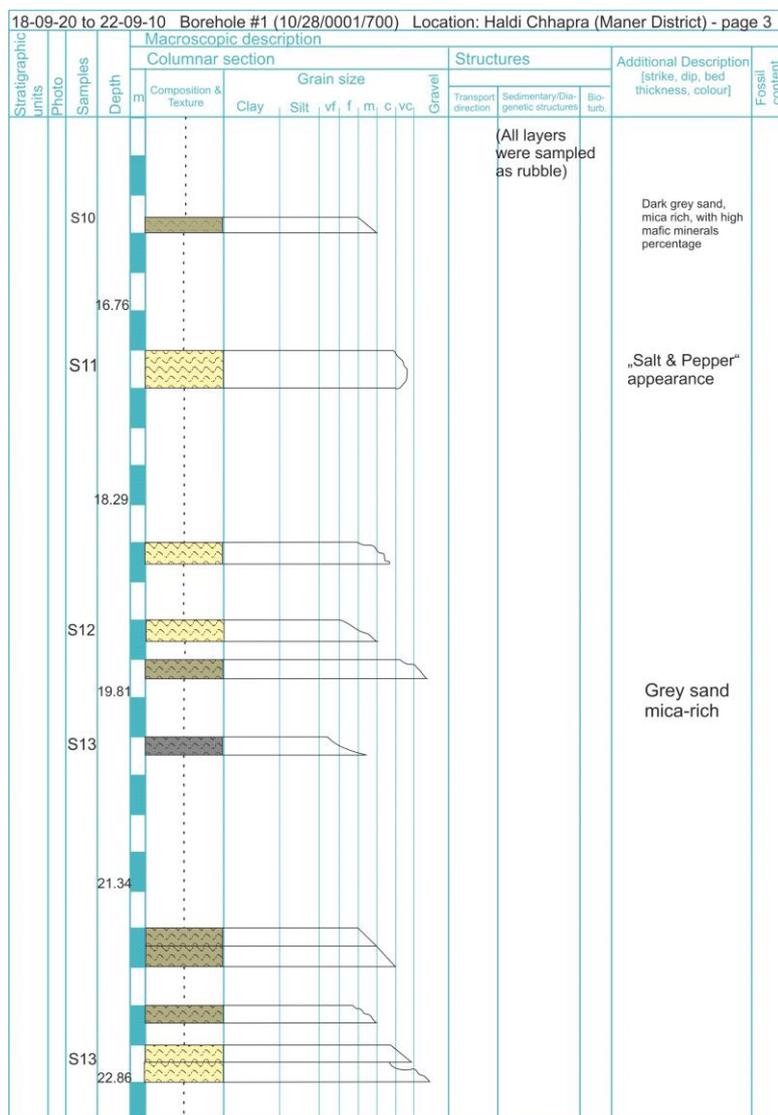


Figure 33 Part of stratigraphy in Borehole #1, as it was initially designed.

Each bar indicates the depth at which the sample was obtained. The thickness of the bar does not respond to real layer thickness and it was arbitrary chosen to be 6 inches. This way of illustrating the results, despite demonstrating what was exactly encountered while drilling, it contains gaps between the obtained data that still needed to be filled, in order to form a complete description of the stratigraphy and to determine the various lithofacies.

In order to achieve this, data were extrapolated in accordance with observations made on field, thorough literature study of the Middle Ganga Foreland Basin geological characteristics and stratigraphy and after understanding the depositional patterns of the Ganga River.

The result that was obtained, for the same part of the borehole that is shown in Figure 33, is demonstrated in Figure 34.

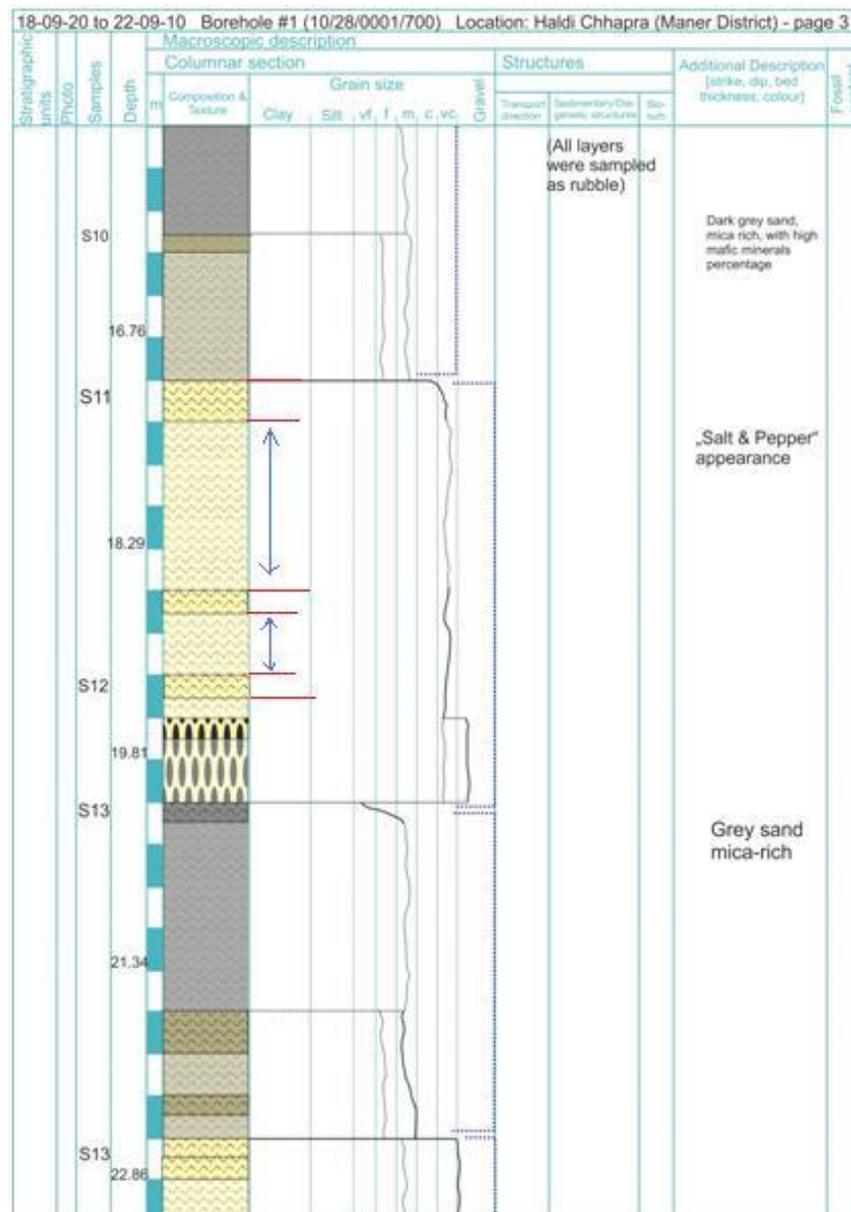


Figure 34 Part of the stratigraphy in Borehole #1, as it was redesigned, after vertical data extrapolation.

The layers with bright colors (indicated in Fig. 34 with red lines) are the ones that were originally obtained and registered while drilling. The layers in faded color between the previous ones (indicated in Fig. 34 with purple arrows) are data that have resulted from extrapolation. The blue dotted line at the right of the grain size description indicates the different layer sequences. The dotted black line and the solid black line in the grain size description show the grain size variation within a layer sequence, as observed while drilling.

As it can be seen in Figure 34, the registered data are now continuous and they resemble a stratigraphic column. By reading this log, one can obtain a much better idea of the stratigraphy and layer properties in the subsurface of Maner.

The data extrapolation procedure included that the symbols for some layers were corrected, according to the description written when the sample was obtained on field, so as to ensure that the correct color and grain size are registered in the log. After this, the stratigraphic column was studied and compared with the other boreholes and with stratigraphic data that were obtained during my personal communication with other researchers. This way I would be able to distinguish the different layer units and stratigraphic sequences. Finally, the data were extrapolated according to the following factors:

1. A layer was extrapolated between two similar observations in order to form a continuous layer, as it is shown in the following illustration. This is based on the fact that while on field, samples were registered in the log only if a change in grain size or color was observed. As a result, a large gap between two registered observations means that the layer is continuous from one to the other (Figure 35).

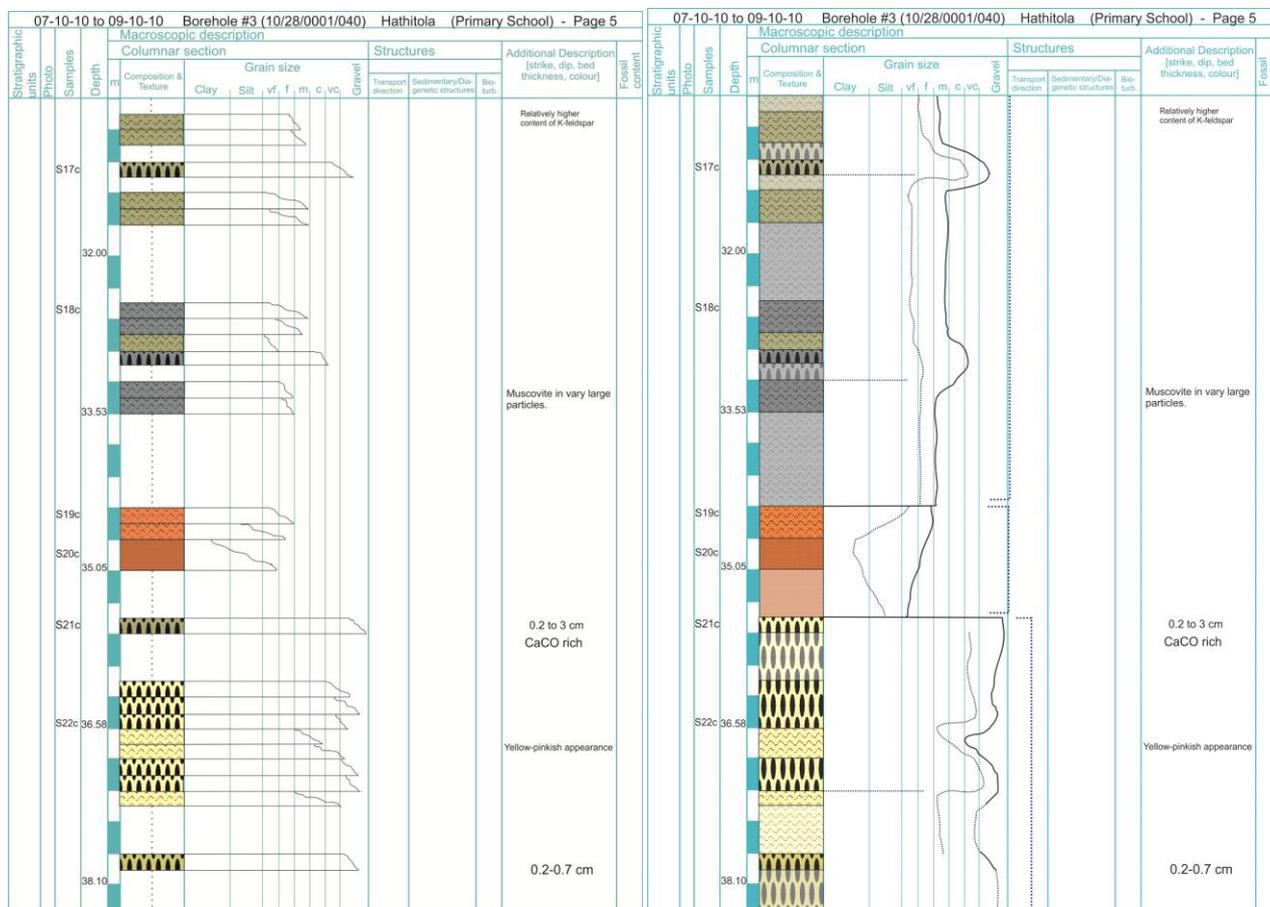


Figure 35 Data extrapolation between two layers that were originally registered as discontinuous. The original design is demonstrated in the left image. The final design (seen in the right image) shows continuous layers that give a better representation of the stratigraphy.

2. Data were extrapolated, according to literature references that may include observations by other researchers, layer thicknesses or sequence descriptions regarding grain size variation among the sequence (whether the grain size and thickness increase or decrease towards the top or the bottom of a sequence).

The above methodology is entirely based on the observer's judgment, experience and knowledge over the geological and stratigraphic regime. This implies that there are increased chances of errors while extrapolating the data. Accurate correlation of the results can only be achieved if an undisturbed core is obtained while drilling.

3. During drilling, especially when the 3rd borehole was drilled, samples were obtained in successive buckets with more accuracy, due to experience gained from drilling the previous boreholes. The samples that were collected in the buckets demonstrated the grain size variation and changes in layers within every 5 feet, when the boring tube

would be cleaned by flushing out the sediment, but did not provide any information regarding the layer thickness. Some parts of the bore logs have been vertically spread in order to fill in the stratigraphic column, as shown in Figure 36, but as with all sand samples, the layer thickness is only indicative and has been derived by observations made while drilling.

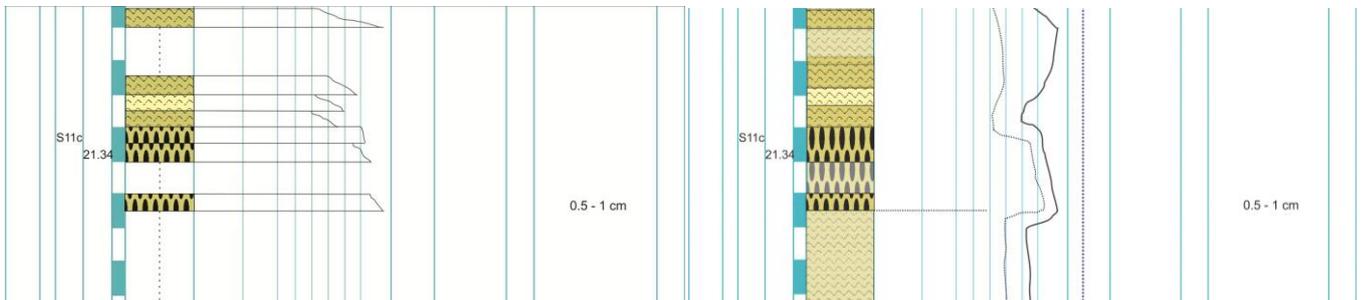


Figure 36 Data spreading within each 5 feet and indication of grain size fluctuation. The initial design can be seen in the left image, while the final one is demonstrated in the right one.

- Observations that were marked on log paper as different layers were grouped in one layer and then organized in distinguished units. Instead of bars indicating the variation of grain size within each thin layer, a continuous line is drawn next to the stratigraphic column, which shows the fluctuation of grain size with depth. This can also be observed in the figure above.

Stratigraphic description of Maner

This paragraph gives the description of all the layers that were encountered while drilling in the area of Maner (Tables 6 and 7). Details regarding the layers are included in the bore logs in Appendices E, F and G.

Soil layer	Type	Color	Grain Size and Shape	Mineralogy ¹	Description
S1	Sand	Grey	Very fine to medium sand, subrounded	Quartz, plagioclase, Muscovite, biotite	Typical Ganga River channel deposits. The highest arsenic concentration was measured, both in the sediment and in the aquifers within it (>800 ppb). Possibly point bar deposits.
S1A	Sand	Dark gray	Fine to medium sand, subrounded	Same with S1, but contains very high muscovite percentage	
S2	Sand	Brown-red	Very fine to fine sand, subangular	K-feldspars, quartz, plagioclase	Unique deposits that exist only in the conjunction of Ganga River with the Sone River. They form one very thin layer spread throughout the research area. Around borehole 1 it has been discovered that they are also Arsenic affected.
S7	Sand	Yellow	Medium to very coarse sand, subangular	Quartz, K-feldspars, calcite, biotite	Typical Sone river channel deposits. Mostly Arsenic free.
S7B	Sand	Yellow	Medium to coarse sand, subangular	Same with S7, but higher muscovite content	
C1	Clay	Gray	-	-	Ganga River floodplain deposits or caps of point bars.

Table6 Description of the various layers that were encountered while drilling (part A).

¹ Mineralogy is given according to macroscopic observation of both wet and dry samples on field and in the laboratory. XRD and SEM tests are going to confirm or reject these estimates.

Soil layer	Type	Color	Grain Size and Shape	Mineralogy ²	Description
C2	Clay	Brown	-	-	Sone river floodplain deposits. It is considered to be source of arsenic.
C4	Clay	Dark gray to black	-	-	Lacustrine depositional environment, strongly anoxic. Oxbow lakes or point bars of the Ganga River. Arsenic is probably formed within these facies.
G1	Gravel	Gray	0.2 to 0.3 cm, subrounded	Quartz, plagioclase, Muscovite, biotite	Coarser parts of the above mentioned sand and clay sequences. Iron coated quartz or biotite grains are present in these layers.
G1A	Gravel	Dark gray	0.2 to 0.3 cm, subrounded, rarely subangular	Same with G1, but contains very high muscovite percentage	
G2	Gravel	Brown, red and yellow	0.2 to 0.3 cm, subangular	K-feldspars, quartz, plagioclase	
G7	Gravel	Yellow, light gray and white	0.2 to 0.4 cm, subangular	Quartz, K-feldspars, calcite, biotite	
G7B	Gravel	Green, yellow and light gray	0.2 to 3 cm, subrounded to subangular	Same with G7, but higher muscovite content	
PI	Clay and sand	Brown and off-white	Varies from clay size to gravel of 0.5 cm length. Subrounded to rounded.	Calcite, quartz, clay minerals	

Table 7 Description of the various layers that were encountered while drilling (part B).

The mineralogical description that is provided in the previous tables was later enriched with Scanning Electron Microscopy data. The SEM results are included in the bore logs (appendices E, F and G) and the methodology that was applied is presented in the following paragraph. These results in general agree with the observations that were made on field. It is important to add that samples S1, S1A, C1 and C4 of grey sand or clay that have high mica content, also contained ilmenite, which could not be recognized on field. In addition, Zr and rare earth minerals were observed in some of these samples.

² Mineralogy is given according to macroscopic observation of both wet and dry samples on field and in the laboratory. XRD and SEM tests are going to confirm or reject these estimates.

Borehole data correlation and lateral spreading

Lateral spreading of the borehole data could be carried out accurately only for clay layers. There are two reasons for this.

First of all, clay is mostly deposited in sheets that cover extended areas within the floodplain of a river, while sand deposits are usually confined within the channel or near it, usually forming depositions that are lense-shaped and therefore of smaller extend. The distance between the boreholes is 1.6 to 3 km. This distance is too large to allow a possible correlation of sand layers between them.

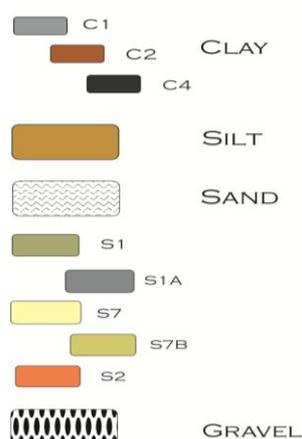
In addition, clay layers could be registered in the borelogs more accurately and could therefore be securely identified and distinguished. Thickness of clay layers could also be accurately registered in the borelogs, while sand layers were poorly registered both in terms of layer thickness and in terms of sedimentary structures, since they were obtained in a slurry form.

Figures 37 and 38 give two possible scenarios regarding the correlation of clay layers among the three boreholes.

Scenario No. 1 (Figure 37) suggests that some of the clay layers are not continuous, but form less extensive depositions within thicker clay layers. Clay layers C7 and C1 (see Tables 6 and 7) contained a high percentage of silt or sand and estimating their dimensions is therefore uncertain. In addition, these layers were encountered in all three boreholes, in similar depths, but with slight differences in their characteristics, mostly regarding the amount of sand that they contained. In some cases, the depths could not be properly correlated, but this may as well have occurred due to the general inaccuracy of the drilling method. The C4 clay layer (see Table 7), which can be seen at the lower parts of the clayey sequence with dark grey to black color, was also considered as discontinuous, because it contained a high amount of organic material and sand in different percentages from one borehole to the other.

In Scenario No. 2 (Figure 38), layer C4 is considered as continuous within a thicker clay succession. This scenario supports that although the properties of this layer are slightly different from one borehole to the other, it is indicative of an extensive swamp deposition, due to its high organic content and can therefore be considered as one continuous sheet of clay.

LEGEND



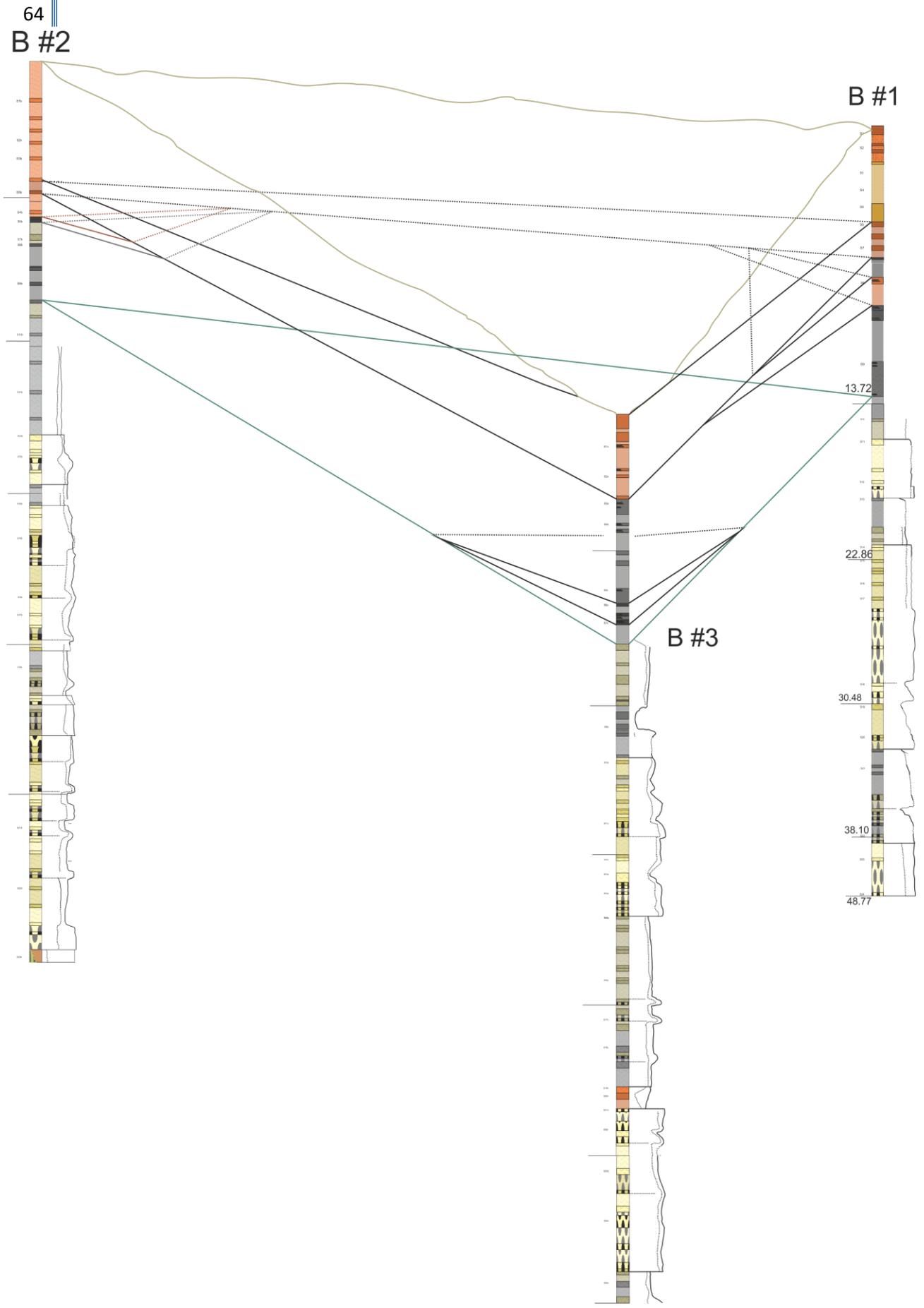


Figure 37 3D section showing possible correlation of clay layers between boreholes. Scenario No.1

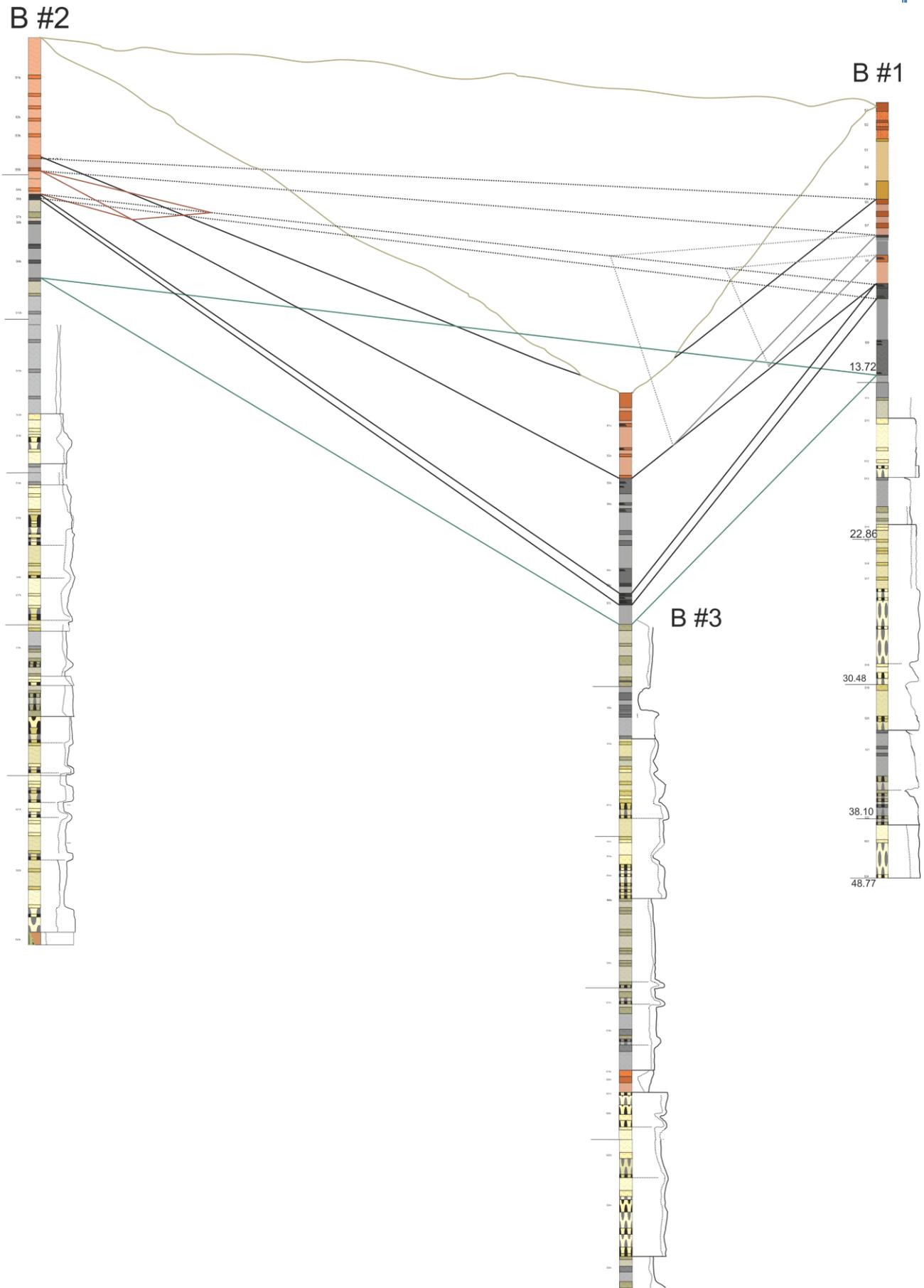


Figure 38 3D section showing possible correlation of clay layers between boreholes. Scenario No.2

Laboratory testing

Due to mostly financial reasons, laboratory testing was carried out in different laboratories and research institutes. This paragraph gives a short description of the methodologies that were applied in laboratory analysis.

Ultra Violet Spectrophotometry

Arsenic concentration in sediments was estimated in the laboratory of A.N.College, Patna, by using a UV Spectrophotometer. The following sample preparation and testing method was applied:

Five grams of soil sample were taken in a 100ml conical flask and 50 ml of 0.5M NaHCO₃ solution was added. Then the whole material was shaken for 2h in a “to and fro” horizontal shaker and after completion of shaking, the suspension was filtered through Whatman filter paper No. 42. The filtrate was collected for arsenic analysis through Silver Diethyl Dithio Carbamate Method (SDDC) using an Ultra Violet Spectrophotometer.

Arsenic extraction from the soil was carried out according to the Silver Diethyl Dithio Carbamate Method. The chemical reagents that were used in order to extract the Arsenic from the soil were Hydrochloric Acid (HCl), Potassium Iodide solution (KI) (15%W/V), Stannous chloride reagent (SnCl₂) (40% W/V), Lead acetate solution (10% W/V) -Dissolved 10 g Lead Acetate Pb (C₂H₃O₂)₂, SDDC (Silver diethyl dithiocarbamate) (0.3%W/V) and Arsenic free zinc granules (3 gm for each sample).

For the estimation of arsenic, 100 ml arsine generator and 35 ml of digested soil sample were taken in a flask. Five ml of concentrated hydrochloric acid and 2 ml of potassium iodide solution were added to the flask. The flask was whirled gently to mix and allowed to stand for one minute. Then few drops of stannous chloride solution (approximately 0.5 ml) were added until the solution became transparent. A piece of cotton wool, moistened with a few drops of 10% lead acetate solution was placed tightly into the proximal absorber part and attached with the generator. After 15 minutes of the reaction, 5 ml of SDDC reagents were taken through the open-end test tube of the distal absorber part. Three grams of granular zinc pellet was added to the generator flask and the double bend absorber part was connected immediately to ensure that no gas could escape from the system. After a few minutes the reaction took place releasing gas in the generator flask. The gas passed through the yellow color SDDC reagents.

The reaction was allowed to continue until the bubbling paused (approximately 30 minutes). After 30 minutes, the coloring reagent (SDDC solution) was transferred into a 5 ml volumetric flask and filled with chloroform. Finally, arsenic concentration was measured at 520 nm in the Ultra Violet Spectrophotometer.

X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM)

XRD testing and SEM images were assigned to the Departamento Da Engenharia, Aveiro, Portugal. According to the minerals that were observed on field, testing in SEM and XRD was instructed. This means that each sample was tested for different elements, chemical composition and mineralogical composition. Details regarding the elements and minerals that were tested are given in Appendix H. The XRD results were of no use for the present research.

Additional SEM testing was carried in Delft University of Technology, in the Department of Geotechnology, faculty of Civil Engineering and Geosciences.

The equipment that was used is a JEOL 8800 M Electron Probe Micro-Analyzer.

The instrument uses a Tungsten-filament to generate an electron beam at high vacuum. It is equipped with three wavelength dispersive spectrometers with LDE1, TAP, PET and LIF analyzing crystals. These analyzing crystals define a possible identification range of elements from Carbon (C) to Uranium (U).

Samples were coated with carbon (C) in order to enhance electrical conductivity. Carbon coating have a thickness of approximately 30 Angstrom. Qualitative analyses were carried out at 20KV accelerating voltage, in order to excite electrons by all elements in the detectable wavelength range. Backscattered Electron Images (BEI) of loose grains besides relief, also show the mean atomic number information. This is used to detect grains with values that exceed the average mean atomic number.

Identification of elements that participate in the sample composition was done automatically, with, if necessary, manual corrections or additions.

Besides the above mentioned laboratory tests, X-Ray Fluorescence was also applied on a number of samples in order to detect As, Fe and Mn. XRF testing was carried out by Ruud Hendrikx in the X-Ray Facilities of the Department of Materials Science and Engineering, Faculty of 3mE, Delft University of Technology. After testing an indicative number of samples, it was shown that arsenic existed in percentages below the detectable limit of 50 ppm.

Results implementation

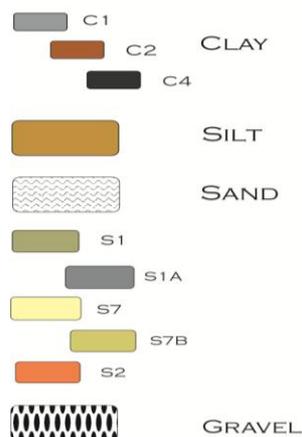
Table 8 shows the average arsenic concentration for each one of the sand or clay types that were distinguished in the area (details regarding the layer characteristics are presented in Tables 6 and 7). As it can be seen in Table 8, the highest arsenic concentration was measured in the Ganga depositions. More specifically, the sand of S1A type and the clay layers of C1 and C4 type show a relatively higher arsenic concentration.

Layer	Average Arsenic concentration ($\mu\text{g/g}$)
C1	0,996
C2	0,295
C4	1,107
C7	0,495
Silt2	0,467
S1	0,268
S1A	1,190
S2	0,357
S7	0,206
S7B	0,281
G1	0,308
G7	0,357
G7B	0,098

Table 8 Average arsenic concentration in each layer in ppm, as derived by UVS testing.

More analytically, the graphs that follow (Figures 39, 40 and 41) show the concentration of arsenic with depth in the three boreholes. The concentration is indicated with the first number next to each measurement point, while the brackets that follow the concentrations, refer to the layer type. Due to several inconsistencies while testing with UVS, the arsenic concentrations that were measured were much lower than what was expected according to literature and previous studies in similar sediments. Therefore, they will be used as a comparative indication of arsenic levels in the different layers, rather than absolute measurements of arsenic concentration.

LEGEND



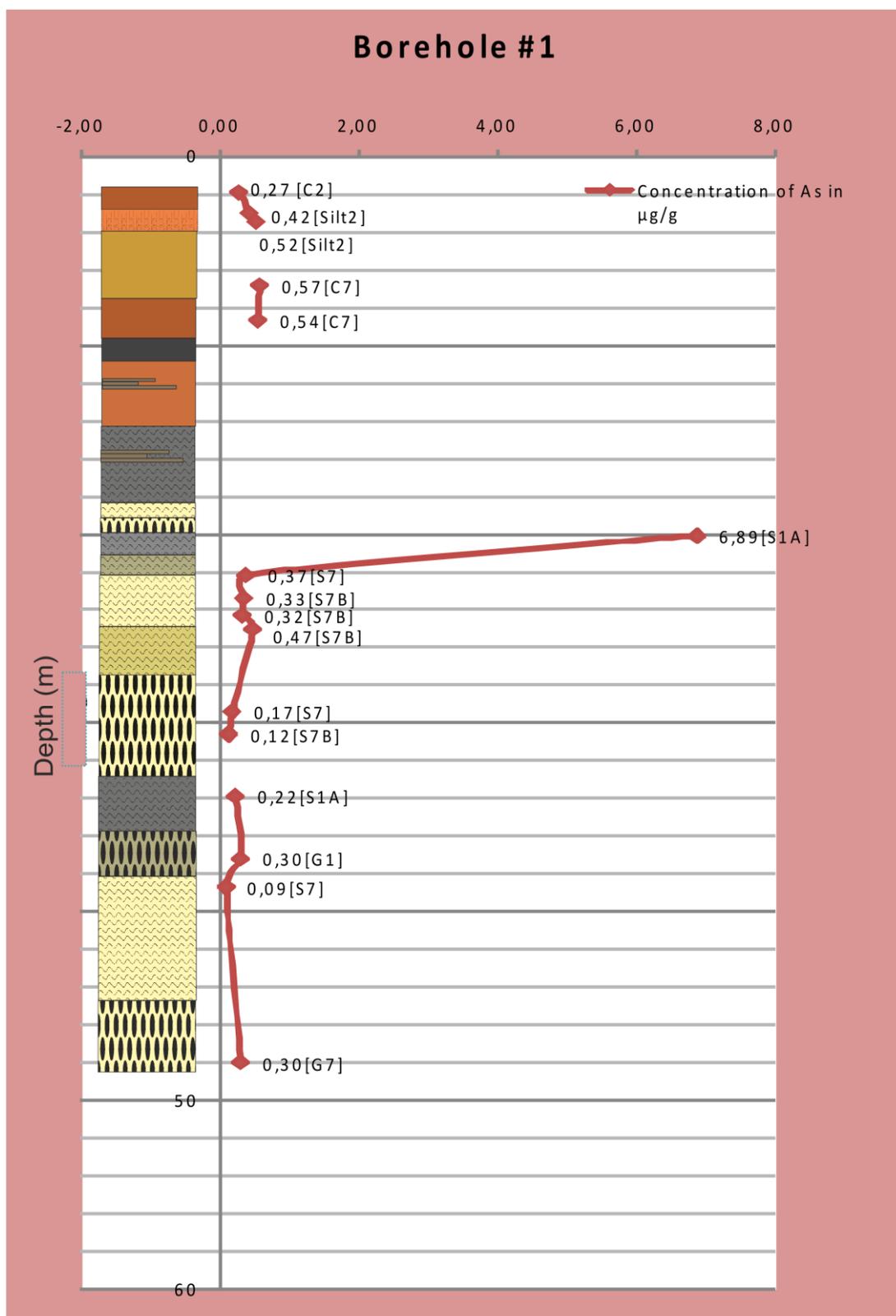


Figure 39 Arsenic concentration with respect to depth, along Borehole #1.

In Borehole #1 (Figure 39), it is worth noticing a peak of arsenic concentration shows in layer S1A, dark gray sand, deposited by the Ganga River, which is muscovite and biotite rich. This concentration is the highest encountered in all three boreholes. The top layer succession of C7 clay and Silt show also relatively high arsenic concentrations. A relatively higher arsenic concentration is also encountered between 38 and 40 m depth, in the G1A layer, which actually is the coarser bottom part of the S1A sequence.

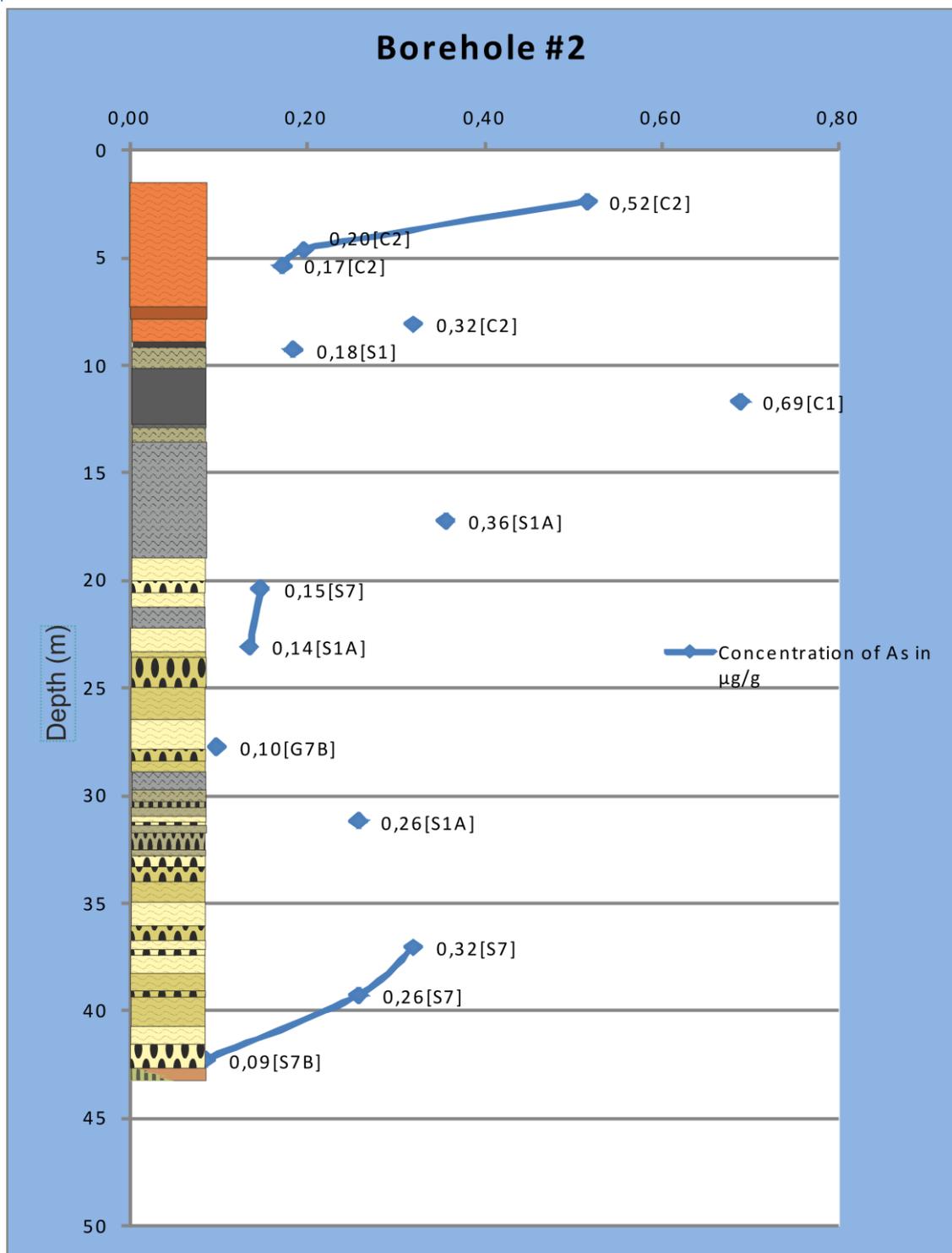


Figure 40 Arsenic concentration with respect to depth, along Borehole #2.

In Borehole #2 (Figure 40) the highest arsenic concentrations are encountered in layers C1 (dark grey clay), which is a cap layer of S1 and S1A sand. The S1A layer also shows a relatively higher arsenic concentration. Finally, at the depth of 37 m, the sand layer S7 also shows a relative peak of arsenic concentration.

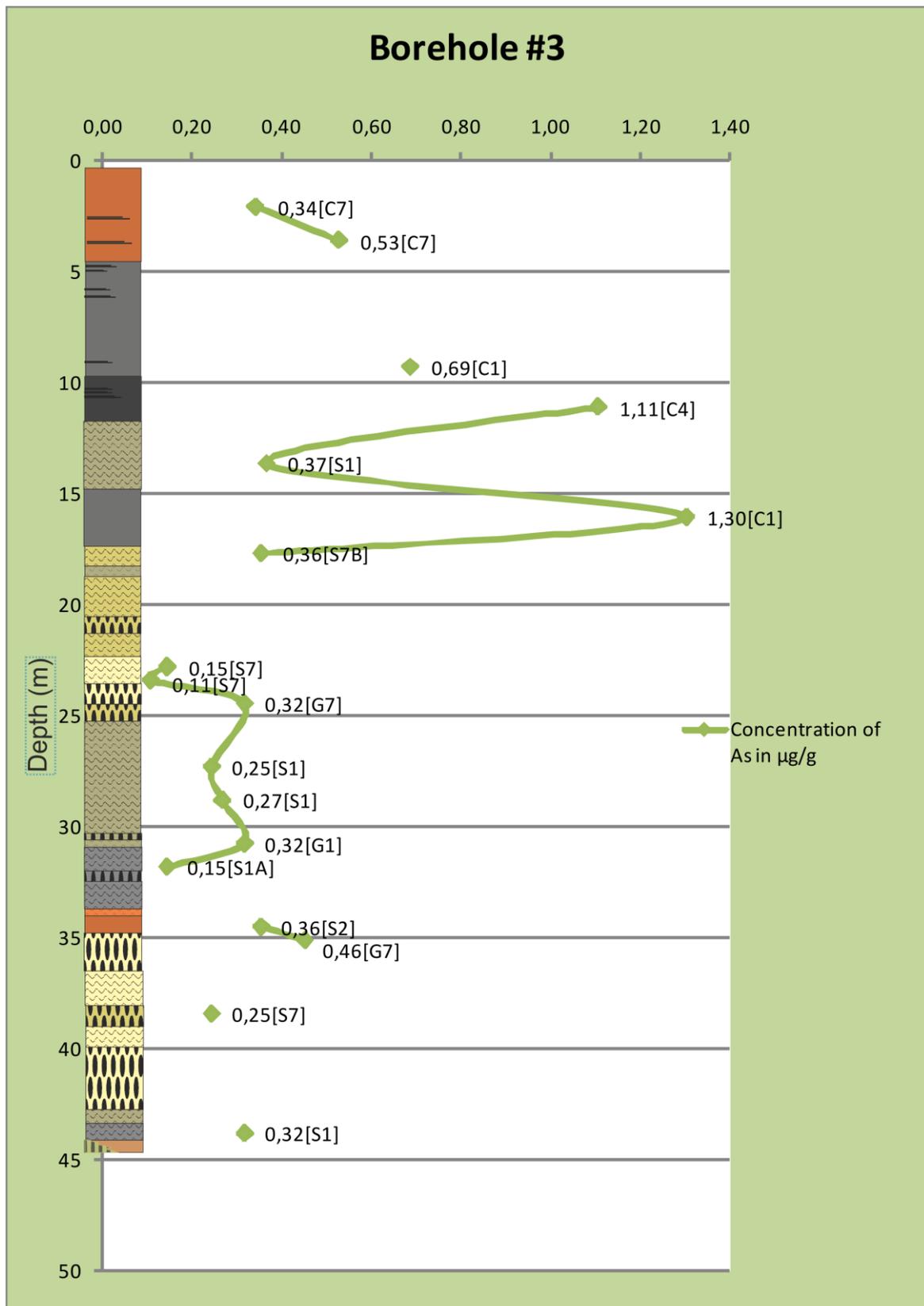


Figure 41 Arsenic concentration with respect to depth, along Borehole #3.

In Borehole #3 (Figure 41), arsenic concentration is significantly higher in clay layers C1 and C4. At the lower parts of the borehole, layers G7 and G1 also show slightly higher arsenic concentrations.

Conclusions and discussion

The results of this research do not falsify the hypothesis that was initially stated. Moreover, they provide with interesting details regarding the geologic and mineralogical origin of arsenic in the groundwater.

Arsenic is confined within the Holocene sediments. Arsenic concentrations in the groundwater also indicate that the Pleistocene aquifers are relatively arsenic free.

Iron oxides may be the source of arsenic in the groundwater. Iron coatings were detected by SEM testing, mostly on quartz and clay grains in some specific layers. Biotite was also detected in abundance mainly within the Ganga River deposits.

Consequently, both iron coated quartz and clay grains and/or biotite may be responsible for the existence of iron oxides in the sedimentary environment, which are crucial for sorption of arsenic on them.

The UV Spectrophotometry method that was applied was only able to extract and detect a fraction of the arsenic that is contained in the soil. NaHCO_3 is one of the most appropriate solutions that can be applied during the digestion process to extract an important amount of arsenic from the soil sample. By observing the arsenic concentration curves that were obtained during similar research though, it can be digested for one or two hours, as it was done during our research, only a fraction of the arsenic content can be measured (Hossain, Akai, & Sahugawa, 2004). In order to determine the exact total arsenic content, the same methodology needs to be applied for a longer time period, which was not possible due to time limitations.

For the purpose of this research though, it was assumed that the initial arsenic release while testing is proportional to the arsenic content of the soil (Hossain, Akai, & Sahugawa, 2004) and was therefore used as an indication of relative levels of arsenic in the sediments. This assumption needs to be validated in future research.

The UV Spectrophotometry analysis showed that the Ganga River deposits (C1, C4 and S1A) have relatively higher arsenic levels than the deposits of the Sone River. The above mentioned sequence of clay covering the sand layer indicates the presence of a reductive environment and a sequence of possible abandoned point bars or oxbow lakes of the Ganga River.

The highest peak in arsenic content was found within a sandy deposit of S1A type. The S1A sand is dark grey (an indication of reductive environment) with very high mica content (biotite and muscovite) that also contains Rare Earth Elements. Minerals containing Rare Earth Elements are not a source of arsenic, but Rare Earth Elements coincide with the existence of arsenic in sediments, since they are both released by iron oxyhydroxides.

The S1A layer has been deposited by the Ganga River and the stratigraphy of the area indicates that it belongs to point bar deposits.

The previous observations suggest the following source and release mechanism for the region of Maner:

Arsenic probably originates from ore zones of the Himalayas. These zones are eroded by the Ganga River and its tributaries and the sediments are then transported and deposited along its course.

Arsenic is released by the weathered minerals that originally contained it (ore minerals have a very low resistance to weathering) and is then sorbed on the surface of clay particles and Fe oxyhydroxides within the C1 and C4 formations (Fig. 42).

Under reductive conditions of a lacustrine environment and with a high amount of organic material acting as a reagent, reductive dissolution of Fe took place, which lead to the release of arsenic in the groundwater (Fig. 42).

The S1A sand lense, which is a point bar deposit, comprises a confined aquifer that is located between the C1 clay and overlies previous floodplain deposits. The C4 lacustrine deposits are part of an adjacent oxbow lake. Arsenic was released and evidently trapped in the groundwater of the aquifer in the point bar, which explains why the S1A sediment is enriched in arsenic.

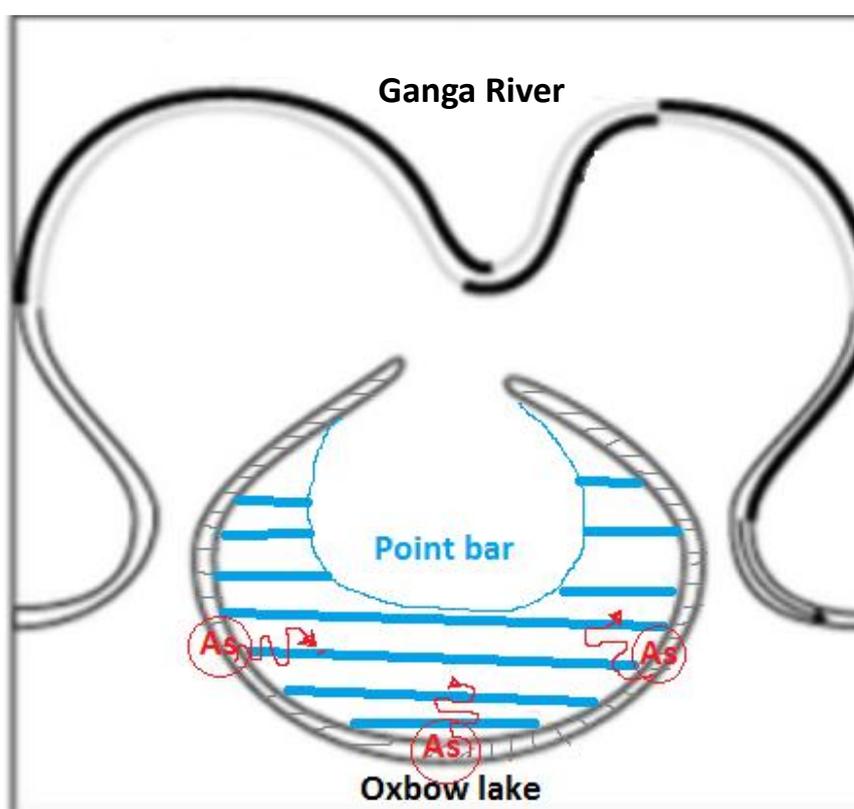


Figure 42 Simplified oxbow lake-point bar system that shows how arsenic was released from the first environment and transported due to groundwater flow to the second one. This probably occurred when the sedimentary features were already covered by more recent depositions of the Sone or the Ganga River.

The results of the XRD and XRF testing suggest that they are not suitable for detecting arsenic in sedimentary soil samples, because of the low level of arsenic contained in them. Arsenic content that is lower than 50 ppm cannot be detected in the soil samples via these methodologies.

A more detailed study of the hydraulic parameters of the subsurface by conducting further geophysical research (aquifer mapping) and drilling (undisturbed sampling and testing for hydraulic parameters) can add useful data to the existing ones. By knowing these parameters, flow modeling can be carried out and the exact mobilization path for arsenic can be identified. Rotary drilling, sonic drilling, hand augering and vibracoring are some methodologies that could be applied in order to obtain undisturbed soil samples. The last two have the advantage of being portable and relatively cheaper and easier to apply, but they only reach a limited depth (usually up to 10 m).

Time interval between sampling and testing may affect the results of the tests. This can be derived by the fact SEM testing on the samples that was carried out one month after sampling detected arsenic in them, while samples that were tested three months later do not show any arsenic content. This needs to be further examined to ensure that future research will be carried out accurately.

Multicultural analysis

One of the biggest challenges that were faced during this research project was to overcome issues that may arise from cultural differences. Experience gained through engineering projects on developing countries has shown that by ignoring cultural differences, problems may occur that will affect both the projects outcome and its sustainability.

From the beginning of the project there was a series of misunderstandings between me and the Indian partners, which was a result of use of different scientific language. One striking incident is the one of the drilling technique that was applied.

It was agreed that hand drilling would be applied. When I arrived on site in Patna to observe the first drilling, I realized that what I expected by hearing the term “hand drilling” was far from what would actually be practiced. In Europe it is common to use this term for hand augering, while in India “hand drilling” refers to man-powered percussive drilling. It was my first encounter with cultural differences, as far as this project is concerned and the triggering event for me to include this chapter in my Thesis.

I will give a short description of Bihari culture and an outline of Hofstede’s Cultural Dimensions for India, along with everyday life examples that demonstrate them, as observed by a female student of Greek origins, studying in a Dutch university, working on a research project in India.

Bihari culture

The official languages of Bihar are Hindi and Urdu, although Bihari languages, like Angika, Bajjika, Bhojpuri, Magahi and Maithili, are widely spoken, especially in the rural areas.

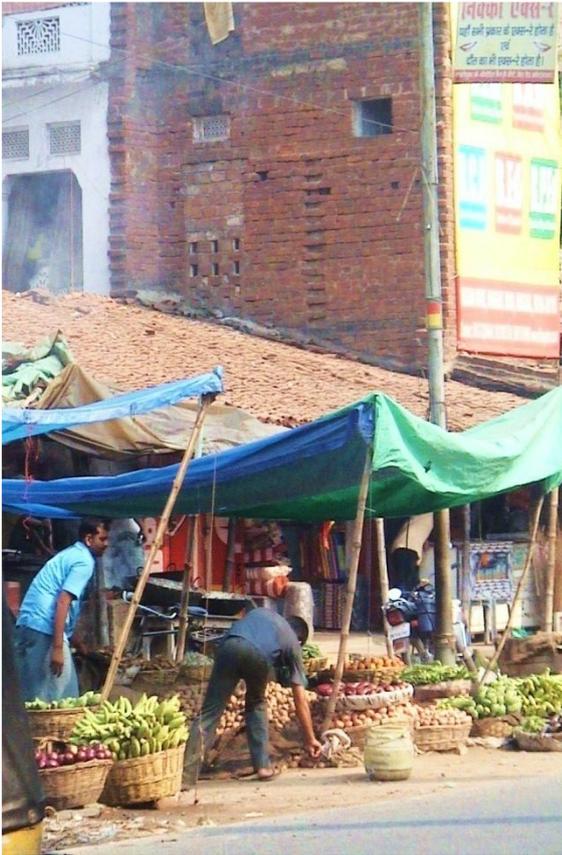
Bihar has excelled in cultural expression such as writing, dance, sculptures and Hindi classical music, but the most famous art crafts that originate from it are the Madhubani paintings. Madhubani painting is a style of Indian painting, practiced in the Mithila region of Bihar. Tradition states that this style of painting originated at the time of the Ramayana. Madhubani painting mostly depict nature and Hindu religious motifs. Natural objects like the sun, the moon, and religious plants like tulsi are also widely painted. Traditionally, painting was one of the skills that were passed down from generation to generation in the families mainly by women.

Bihar may be called the cultural cradle of Indian civilization. Its rich heritage dates back to very ancient times. The religious basis of both Buddhism and Hinduism were formulated by Buddha and Mahavira in the plains of North Bihar. The great center of Buddhist learning in Nalanda and several centers of cultural and religious interest attract visitors from all over the world.



Figure 43 The famous No Honking sign. Peculiar to the eyes of a foreigner, but essential as far as Indian driving habits are

Social and economic aspects



The economy of Bihar is largely service oriented, but it also has a significant agricultural base. The state also has a small industrial sector. The state is undergoing fast economic development with its impact on life style, natural resources and the environment. Agriculture plays a key role in poverty alleviation, where 90% of the population is rural. The assured availability of water for irrigation is the key factor of shaping the future economic scenario of the state, where the future pressure for irrigation and safe drinking water will be from the groundwater.

Bihar has great ancestry of metallurgy and mining, as evidenced by numerous ancient underground workings. Several minerals like metallic minerals of iron, copper and gold, to non-metallic mica, clay, ochres and soapstone have been mined. The concept of “uparchala” pitting in prospecting and development of mica pegmatites dates back to ancient times, when the local people had developed techniques of mining, some of them several tens of meters deep (Mahadevan, 2002).

Bihar has a grossly inadequate educational infrastructure creating a huge mismatch between demand and supply. This problem further gets compounded by the growing aspirations of the people and an increase in population.

Bihar has a very traditional and conservative society, where most of the women above a certain age focus on housekeeping, despite the fact that they may not lack in educational background. Women have only recently started to gain a respectful position in society. This has been largely enabled by support state - provided support for education.

In general, since its independence, Bihar has persistently kept a rather old fashioned way of living, compared to other states of India. Criminality rates have been alarming during the last decades (abduction numbers being one of the most important). In addition, Maoist Naxalites activity in Bihari forests, clashes between communist villagers and right wing land-owners and a rather mob lynching approach to resolve differences, place Bihar correctly among one of the most lawless states of India.



According to citizens of Patna though, the situation has significantly improved since the change of government, five years ago.

This seems to apply only for the capital and major urban areas, unfortunately, while the rural areas are still highly neglected.

Hofstede's five Cultural Dimensions

This paragraph gives a short introduction to Five Cultural Dimensions, as they were introduced by (Hofstede, 2004), in order to describe effectively the structure of a society and the behavior of its members as a whole. These Dimensions aim to describe the behavior of the members of the society within it and towards its aspects than the societal structure itself.

Power Distance Index (PDI) is the extent to which the less powerful members of organizations and institutions (like the family) accept and expect that power is distributed unequally. This represents inequality (more versus less), but defined from below, not from above. It suggests that a society's level of inequality is endorsed by the followers as much as by the leaders. Power and inequality, of course, are extremely fundamental facts of any society and anybody with some international experience will be aware that 'all societies are unequal, but some are more unequal than others'.

Individualism (IDV) on the one side versus its opposite, collectivism, that is the degree to which individuals are integrated into groups. On the individualist side we find societies in which the ties between individuals are loose: everyone is expected to look after him/herself and his/her immediate family. On the collectivist side, we find societies in which people from birth onwards are integrated into strong, cohesive in-groups, often extended families (with uncles, aunts and grandparents) which continue protecting them in exchange for unquestioning loyalty. The word 'collectivism' in this sense has no political meaning: it refers to the group, not to the state. Again, the issue addressed by this dimension is an extremely fundamental one, regarding all societies in the world.

Masculinity (MAS) versus its opposite, femininity refers to the distribution of roles between the genders which is another fundamental issue for any society to which a range of solutions are found. The IBM studies revealed that (a) women values differ less among societies than men values; (b) men values from one country to another contain a dimension from very assertive and competitive and maximally different from women values on the one side, to modest and caring and similar to women values on the other. The assertive pole has been called 'masculine' and the modest, caring pole 'feminine'. The women in feminine countries have the same modest, caring values as the men; in the masculine countries they are somewhat assertive and competitive, but not as much as the men, so that these countries show a gap between men values and women values.

Uncertainty Avoidance Index (UAI) deals with a society's tolerance for uncertainty and ambiguity; it ultimately refers to man's search for Truth. It indicates to what extent a culture programs its members to feel either uncomfortable or comfortable in unstructured situations. Unstructured situations are novel, unknown, surprising, and different from usual. Uncertainty avoiding cultures try to minimize the possibility of such situations by strict laws and rules, safety and security measures, and on the philosophical and religious level by a belief in absolute Truth; 'there can only be one Truth and we have it'. People in uncertainty avoiding countries are also more emotional, and motivated by inner nervous energy. The opposite type, uncertainty accepting cultures, are more tolerant of opinions different from what they are used to; they try to have as few rules as possible, and on the philosophical and religious level they are relativist and allow many currents to flow side by side. People within these cultures are more phlegmatic and contemplative, and not expected by their environment to express emotions.

Long-Term Orientation (LTO) versus short-term orientation: this fifth dimension was found in a study among students in 23 countries around the world, using a questionnaire designed by Chinese scholars. It can be said to deal with Virtue regardless of Truth. Values associated with Long Term Orientation are thrift and perseverance; values associated with Short Term Orientation are respect for tradition, fulfilling social obligations, and protecting one's 'face'. Both the positively and the negatively rated values of this dimension are found in the teachings of Confucius, the most influential Chinese philosopher who lived around 500 B.C.; however, the dimension also applies to countries without a Confucian heritage.

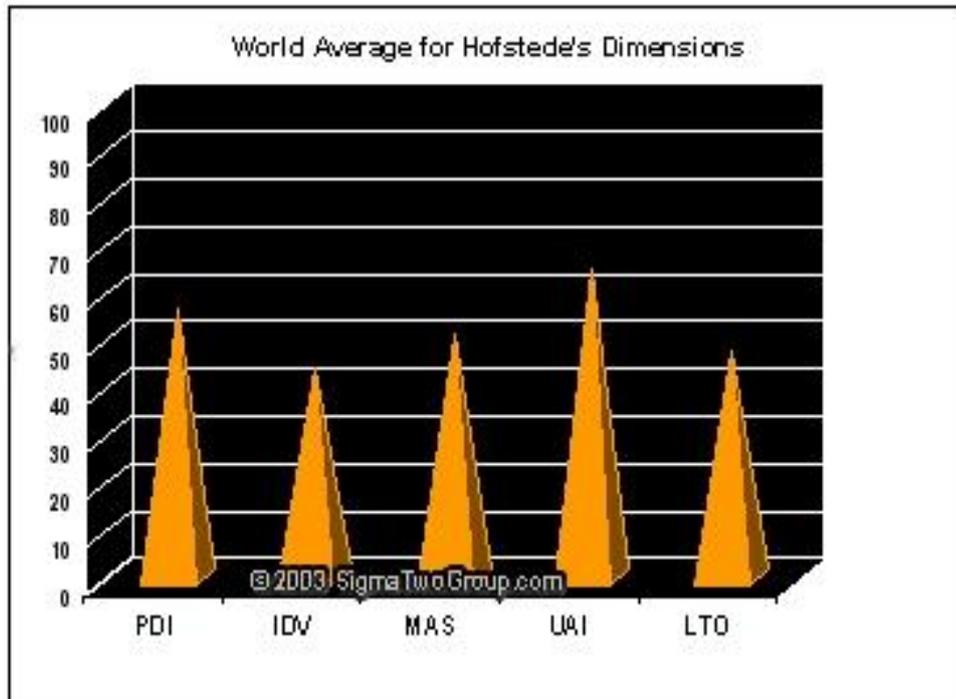


Figure 44 World average values for Hofstede's Cultural Dimensions (Hofstede, 2004).

India's cultural dimensions

Due to its size and variations within it, India is one of the countries that no standard can be established to describe it. It would be rather unfair to say that the cultural Dimensions for India are the same throughout then. This paragraph provides with India's scores and a description of how these were or were not observed during daily life in Bihar, which is a comparatively conservative state, with strong ethical principles.

India has Power Distance (PDI) as the highest Hofstede Dimension for the culture, with a ranking of 77 compared to a world average of 56.5. This Power Distance score for India indicates a high level of inequality of power and wealth within the society. This condition is not necessarily subverted upon the population, but rather accepted by the population as a cultural norm. This cultural dimension of India can be observed in everyday behavior, in small details, for instance people refer to their superiors as "Sir" and "Madam", stand up when they enter a room and in general maintain a rather fearful respect for them. In addition, the caste system that, although not formally recognized by the laws, has always been an essential part of India's social structure, promotes a society that is scaled up to different classes, rather than one where people are equal, since the caste one belongs to, especially in the rural areas, determines the work one can do in large extent and as a result, their social and financial status.

India's Long Term Orientation (LTO) Dimension rank is 61, with the world average at 48. A higher LTO score can be indicative of a culture that is persevering and parsimonious. Maintaining a

family's social status and “good name” is a very important issue, as society often interferes to what individuals do by judging and accordingly approving and praising or disapproving and rejecting, which could directly affect a person's social and professional evolution within a social structure. People in general take seriously into consideration “what will the people around say”. Dignity and integrity are two virtues that need not just to be followed, but also be daily demonstrated. Finally, most Hindu families are very religious, following rituals and beliefs as indicated by their respective religion ethics.

The two Dimensions described above were of great importance for the project course and success. The Power Distance Dimension was observed within the project as well. Formalities and obedience to rules of highly ranked people in order to obtain data from a public service was highly advisable. Direct disagreement was often perceived as a sign of disrespect, although suggestions of alternative solutions were more than welcome. For example, when data were requested from a public service, the people responsible for this would directly agree on providing with it and actually seem very eager to do so. This was rarely the case though, since they sometimes neglected it, they did not have access to them or they were not eager to share data in the first place, but did not want to directly tell. This aspect created an unreliable profile for many of the Public Services involved in the project, as far as data acquisition is regarded, although the people working there were very helpful and informative, when having interviews or discussions with them.

India's Masculinity Index (MAS) ranks third among the Dimensions, at 52, which places India among the “masculine” countries. For Bihar especially, this number could be considered as low. It is a male-dominated and competitive society, where women are mostly expected to behave as housewives, despite their educational background.

Few women have a paid work and in general most of them depend on their husbands not only financially, but also in decisions regarding their personal life. In the rural areas, it is not socially accepted for unmarried women to walk on the streets by themselves. Within the city, this gradually seems to change and groups of schoolgirls and students were regular on the streets. After dusk, women do not have a position in social life. They are not allowed to smoke or drink in public and they are expected not to talk to strangers or be over friendly with them.



Figure 45 Girls attending the public primary school of Hathitola, funded by the local government and UNICEF.

In general, a girl's birth is not always happily accepted in a family, since her safety becomes an important issue as she is growing up and in addition, in most cases, considerable dowry is still required, for a successful marriage to be achieved. This reduces a woman's value in society even more. During the last few years, newly applied governmental policies have been promoting girls' education by providing them with school uniforms and books. In rural areas, schools that are constructed and funded by UNICEF and the local government have established free lunch as a means to attract girls from poor families to attend school, as their parents will be slightly relieved by their expenses.

All the above mentioned regarding a hard-dominated male society imply that without the existence of male students from A.N.College and Ajay Bhatt during fieldwork, this project would have been rather impossible to achieve, if I had to conduct it myself, as a female and a foreigner.

The fourth in ranking Cultural Dimension is Individualism (IDV). India scores 44, which places it among the collectivist countries. Indeed, what could be observed during my stay there is that family members are strongly bonded together, public opinion matters in a large extend and parents are the ones responsible for their children safety and life, often controlling them in a large extend.

India's lowest ranking Dimension is Uncertainty Avoidance (UAI) at 40, compared to the world average of 65. On the lower end of this ranking, the culture may be more open to unstructured ideas and situations. The population may have fewer rules and regulations with which to attempt control of every unknown and unexpected event or situation, as is the case in high Uncertainty Avoidance countries. This is one of the most striking characteristics of the whole country. The widespread concept of *Jugaad*.

Jugaad means improvisation in any form, for any purpose and under any conditions. Indian people have the ability of building anything out of anything and of adapting themselves to any situation. This has resulted from the fact that planning is possible but yet useless, when there are so many factors that may result in changes in your plans. Daily power failures, traffic, lack of maintenance or provided technology are all issues that contribute towards a do-it-your-way direction. This demonstrates society members with preparedness and great innovative and inventive skills, but does not always mean that the result is successful.



Figure 46 Jugaad vehicle.

In addition, low UAI leads people to perceive something different with curiosity instead of disbelief or suspicion. Therefore, even in the rural areas and although the presence of foreigners is very rare in Bihar, I was accepted with warmth and interest regarding my presence there. Hospitality was largely demonstrated both by the people I cooperated with and by the villagers. My presence there was ultimately a great event, especially for the children, who enjoyed being around and observing the drilling procedure.

Bihari rural areas, but also the state capital Patna, is characterized by strict social and behavioral rules that are not so widely applied in other more metropolitan cities of India. In addition, most people refrain from entertainment and leisure activities, the way we perceive them in the West. This might also be a result of Patna's inadequate structure in this, which

deprives students and young people from recreational activities. In general, people are expected to focus on their work, above all.

All the above mentioned social rules were followed during my stay in Patna, which made it more than interesting, but nonetheless restricted, as perceived through the eyes of a western woman. In order to assess these cultural issues to a comparative scale, Cultural Dimension ranks for The Netherlands and Greece will also be presented.

Netherlands Cultural Dimensions

The Hofstede Dimensions for the Netherlands are very similar to that of Scandinavian countries.

The Netherlands highest Hofstede Dimension is Individuality (IDV) at 80. The high Individualism (IDV) ranking for the Netherlands is indicative of a society with more individualistic attitudes and relatively loose bonds with others. The populace is more self-reliant and looks out for themselves and their close family members.

This individuality is integral to in the daily lives of the population and must be considered when traveling and doing business in their Country. Privacy is considered the cultural norm and attempts at personal ingratiating may meet with rebuff.

Due to the importance of the individual within the society, individual pride and respect are highly held values and degrading a person is not well received, accepted, or appreciated.

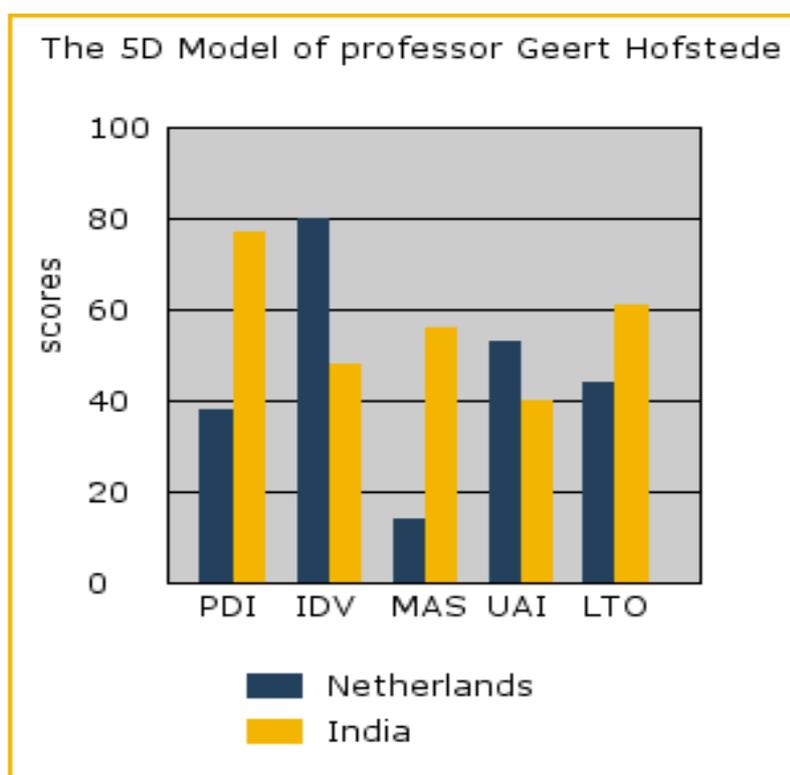


Figure 47 Cultural dimensions comparative scores for Netherlands and India (Hofstede, 2004).

The second highest Hofstede Dimension for the Netherlands is Uncertainty Avoidance (UAI) at 53, compared to the World average of 64. A moderate UAI score may indicate a cultural tenancy to minimize or reduce the level of uncertainty within the population by enacting rules, laws, policies, and regulations to cover most any and all situations or circumstances.

The lowest Hofstede Dimension for the Netherlands is Masculinity (MAS) at 14. This relatively low MAS Index value may be indicative of a low level of differentiation and discrimination between

genders. In this culture, females are treated more equally to males in all aspects of society. This low Masculinity ranking may also be displayed as a more openly nurturing society.

The Netherlands' religious demographics indicate no predominate religion (over 50%) being practiced within the country. However, the largest portion of the population (39%) identifies themselves as Atheist. The next highest practicing group is Catholic at 31%, followed by Christians at 21%, Muslims at 5%, and others with 4%.

Although my nationality is Greek, living and studying in The Netherlands for the last two years has greatly influenced my way of perceiving societal structures and most of all my work schedule and disciplines. Especially the second, brought me into conflict regarding many issues during work that I considered to be different or time consuming. The lack of individualism was also challenging in many ways. I had to learn how to depend on people for matters that concerned the project flow and my personal necessities as well, which often came in conflict with my generally independent way of living.

Greece Cultural Dimensions

Greece scores between Netherlands and India in some Dimensions, while for others it seems to lean more towards India.

Since I have grown up in this country and although I was brought up with relatively open-minded beliefs, some of these values are within my character and way of thinking. This actually helped towards a better integration in the Indian society and in a better understanding and applying of Hindu values in everyday life.

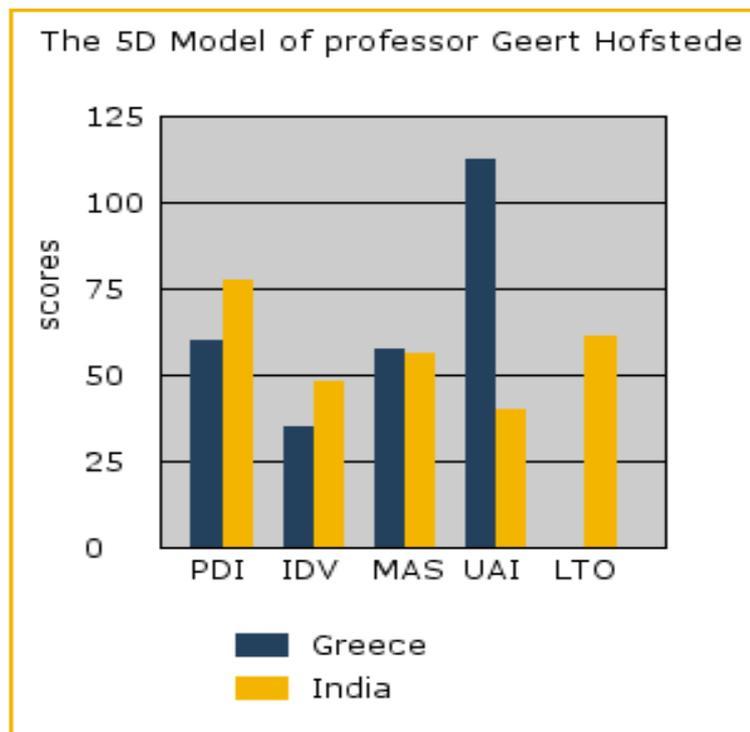


Figure 48 Cultural dimensions comparative scores for Greece and India (Hofstede, 2004).

On the other hand, Greece score in UAI shows differs greatly from the Indian one. As a result, I found myself challenged by the Jugaad concept in many circumstances, which actually contributed in the development of my improvisational and innovation skills on engineering projects.

More pictures demonstrating everyday life in Bihar and social/cultural aspects are included in Appendix K.

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Appendices

Appendix A – ARSENIC AFFECTED AREAS WORLDWIDE

Source: IGRAC, 2008

Country	Region	Origin, natural or anthropogenic (concentration ranges ($\mu\text{g l}^{-1}$))	Ref
Asia			
	Bengal basin	Holocene alluvial/deltaic sediments. Abundance of solid organic matter (<0.5-2500)	9, 1
Cambodia	Mekong delta	Holocene alluvial/deltaic sediments.	9
China	Inner Mongolia (Tumet plain, Huhhot basin, Ba Men, Bayingao, Hexi)	Holocene alluvial and lacustrine sediments (<1-2400)	9,1
	Xinjiang Provinces (Tianshan plain)	Holocene alluvial plain (40-750)	9,1
	Shanxi Province	Alluvial plain	9,1
India	West Bengal (Bengal Basin)	Holocene alluvial/deltaic sediments. Abundance of solid organic matter (<10-3200)	9,1
Japan	Matsu&Turoko	Industrial	A
	Kyushu	Geothermal field	9
Mongolia			A
Myanmar			9
Nepal	Nawalparasi (Western region), Rautahat and Bara (Central), Bardia (Midwestern), Parsa, Rupandehi, Kapilbasthu and Banke	Recent sediments of the Terai region and groundwater of the active floodplain of the River Koshi	B
Pakistan	Indus River		9
Philippines	Mindanao island		12a
Russia	Ural Mountain range	Mine drainage (400.000)	9
	Kamchatka	Geothermal field	9
Taiwan	Southwest and Northeast coastal zones	Sediments, including black shales (10-1820)	9,1
Thailand	Ron Phibun district, Nakhon Si Thammarat Province	Dredged Quaternary alluvium (some problems in limestone), tailing (1-5000)	9
Vietnam	Mekong delta, Red River delta	Holocene alluvial/deltaic sediments. (1-3050)	9
Europe			
Austria			D
Belgium	Schelde estuary	Mining and industry (up to 30)	9,1
Denmark			D
England	Parts of SW England	Mining Pb, Ag	9
Estonia	Parts of NE Estonia	Industrial	5
France	Massif Central	Geothermal field	9
Germany	Bavaria	Upper Triassic Keuper Sandstone (<10-150)	9
Greece	Lavrion	Mining Pb, Ag	9
	Thessaloniki	Geothermal field	1
Hungary	Great Hungarian Plain	Alluvial Quaternary sediments (<2-176)	9,1
Iceland		Geothermal field	9
Lithuania			D
Netherlands	Schelde estuary	Mining and industry	1
Romania	Great Hungarian Plain	Alluvial Quaternary sediments (<2-176)	9
Sweden	Kalix River estuary	Sediment pore water	7
North America			
Canada	British Columbia	Mining (0.5-580)	9
	Saskatchewan	Clay sediments, sediment pore water	7

	Ontario	Mining (35-100)	9,1
	Northwest Territories	Mining (64-530)	9,1
Mexico	Lagunera region, Sonora province, other parts of northern Mexico	Volcanic sediments (Lagunera), calcareous formations (aquifer) (8-620)	9,1
	Zimapan valley	Mining	9
USA	San Joaquin valley, Tulare Basin, California	Holocene and older basin-fill sediments (<1-2600)	9
	Southern Carson desert, Nevada	Holocene mixed aeolian, alluvial, lacustrine sediments, some thin volcanic ash bands (up to 2600)	9
	Basin and Range, Arizona	Alluvial basins, some evaporates (<1300)	9
	Coeur d'Alene district of Idaho	Valley-fill deposits (<1400)	9
	Lake Oahe, south Dakota	Lake sediments (<2000)	9
	Fairbanks mining district of Alaska	Schist, alluvium, mine tailings (<10000)	9
	Coeur d'Alene, Idaho	Pb-Zn-Ag mining	9
	Leviathan mine, California	Mining	9
	Kelly Creek Valley, Nevada	Mining	9
	Clark Fork River, Montana	Mining	9
	Lake Oahe, south Dakota	Mining	9
	Geysir Bight Umnak Island, Alaska	Geothermal field	9
	Honey Lake Basin, California	Geothermal field	9
	Coso Hot Springs, California	Geothermal field	9
	Imperial Valley, California	Geothermal field	9
	Long Valley, California	Geothermal field	9
	Steamboat Springs, Nevada	Geothermal field	9
	Yellowstone National Park	Geothermal field	9
	Lassen Volcanic National Park, California	Geothermal field	9
	South-eastern Michigan		E
South America			
Argentina	Chaco-Pampean Plain	Quaternary deposits of loess (mainly silt) with intermixed rhyolitic or dacitic volcanic ash, often situated in closed basins (<1-5300).	9,1
	Parts of Salta and Jujuy Provinces	Geothermal field	9,1
Bolivia	Southern Altiplano (dept. Potosi)	Geothermal field	1
Chile	Antofagasta area	Quaternary volcanogenic sediments (100-1000)	9,1
	El Tatio system in the Antofagasta region	Geothermal field	9,1
Dominica		Geothermal field	9
Jamaica			C
Peru		Mining	3
Australia			
New Zealand	Lake Ohakuri	Geothermal field	9
	Wairakei	Geothermal field	9
	Broadlands	Geothermal field	9
	Orakei Korako	Geothermal field	9
	Atiamuri	Geothermal field	9
Australia	Southeast Queensland		8
	New South Wales	Industry	10, 2a, 6a

Africa			
Ghana	Ashanti Region, Central Ghana	Au mining	9, 1
Zimbabwe		Mining	9
South Africa		Mining	9

Maps of arsenic distribution worldwide

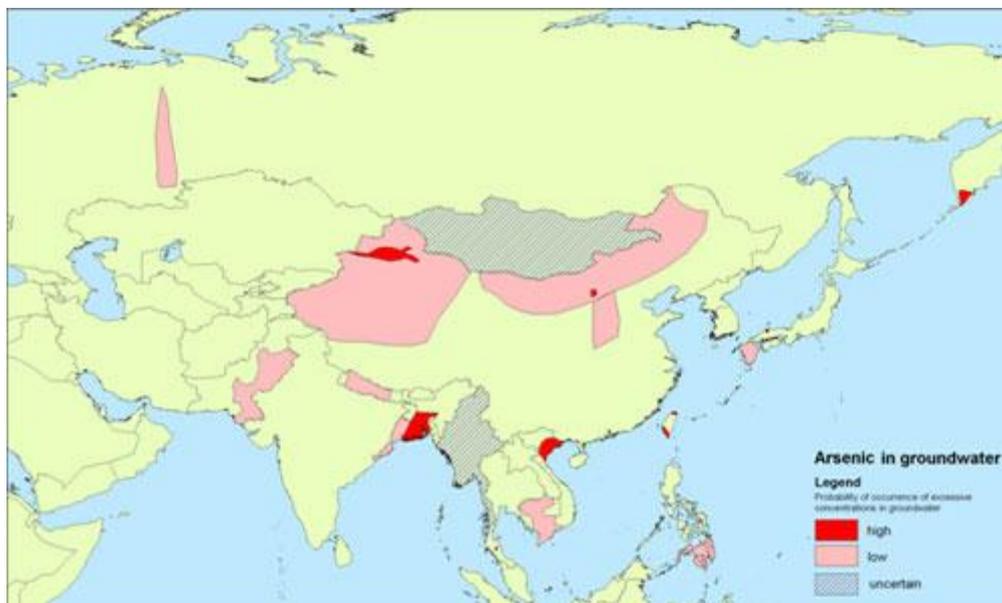


Africa

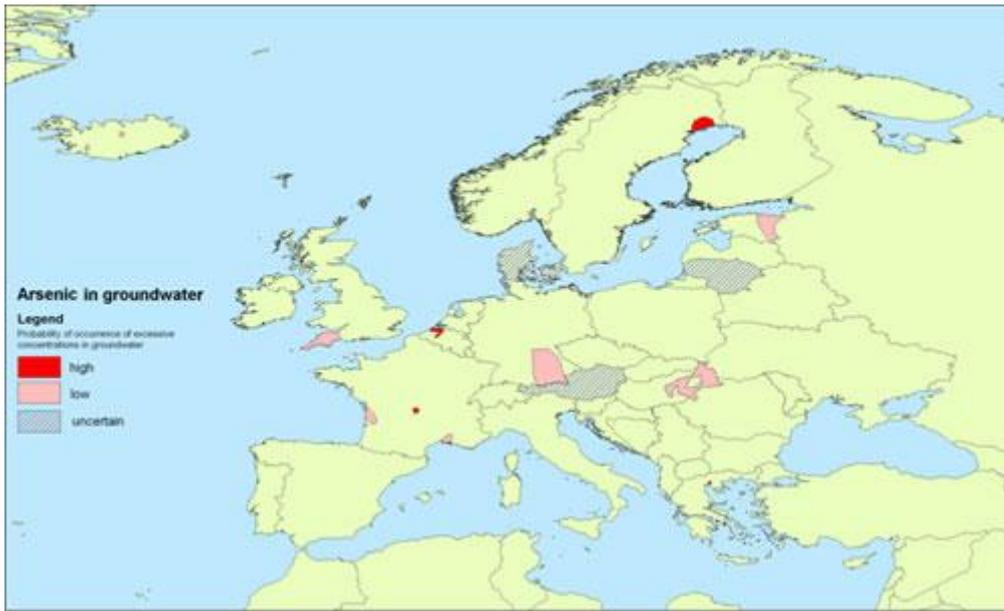
Australia



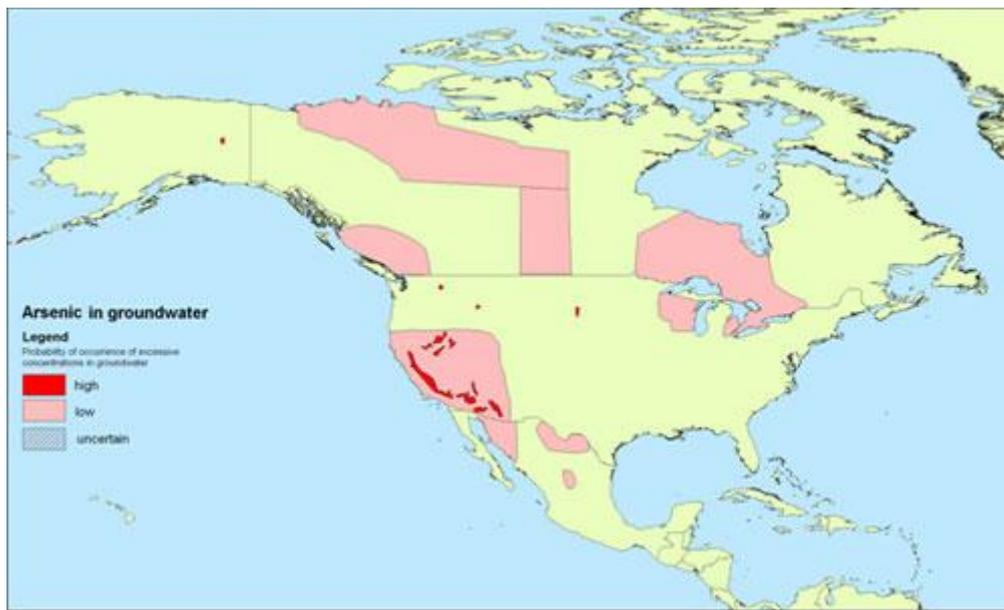
Asia



Europe



North America



South America



Appendix B – Arsenic data according to Smedley et.al. (2001)

Typical As concentrations in natural waters

Water body and location	As concentration average or range ($\mu\text{g l}^{-1}$)	Reference
<i>Rain water</i>		
<i>Baseline</i>		
Maritime	0.02	Andreae (1980)
Terrestrial (w USA)	0.013–0.032	Andreae (1980)
Coastal (Mid-Atlantic, USA)	0.1 (<0.005–1.1)	Scudlark and Church (1988)
Snow (Arizona)	0.14 (0.02–0.42)	Barbaris and Betterton (1996)
<i>Non-baseline:</i>		
Terrestrial rain	0.46	Andreae (1980)
Seattle rain, impacted by copper smelter	16	Crecelius (1975)
<i>River water</i>		
<i>Baseline</i>		
Various	0.83 (0.13–2.1)	Andreae et al. (1983); Froelich et al. (1985); Seyler and Martin (1991)
Norway	0.25 (<0.02–1.1)	Lenvik et al. (1978)
South-east USA	0.15–0.45	Waslenchuk (1979)
USA	2.1	Sonderegger and Ohguchi (1988)
Dordogne, France	0.7	Seyler and Martin (1990)
Po River, Italy	1.3	Pettine et al. (1992)
Polluted European rivers	4.5–45	Seyler and Martin (1990)
River Danube, Bavaria	3 (1–8)	Quentin and Winkler (1974)
Schelde catchment, Belgium	0.75–3.8 (up to 30)	Andreae and Andreae (1989)
<i>High-As groundwater influenced:</i>		
Northern Chile	190–21800	Cáceres et al. (1992)
Northern Chile	400–450	Sancha (1999)
Córdoba, Argentina	7–114	Lerda and Prospero (1996)
<i>Geothermal influenced</i>		
Sierra Nevada, USA	0.20–264	Benson and Spencer (1983)
Waikato, New Zealand	32 (28–36)	McLaren and Kim (1995)
Madison and Missouri Rivers, USA	44 (19–67) 10–370	Robinson et al. (1995) Nimick et al. (1998)
<i>Mining influenced</i>		
Ron Phibun, Thailand	218 (4.8–583)	Williams et al. (1996)
Ashanti, Ghana	284 (<2–7900)	Smedley et al. (1996)
British Columbia, Canada	17.5 (<0.2–556)	Azcue et al. (1994)
<i>Lake water</i>		
<i>Baseline</i>		
British Columbia	0.28 (<0.2–0.42)	Azcue et al. (1994, 1995)
Ontario	0.7	Azcue and Nriagu (1995)
France	0.73–9.2 (high Fe)	Seyler and Martin (1989)
Japan	0.38–1.9	Baur and Onishi (1969)
Sweden	0.06–1.2	Reuther (1992)
<i>Geothermal influenced</i>		
Western USA	0.38–1000	Benson and Spencer (1983)
<i>Mining influenced</i>		
Northwest Territories, Canada	270 (64–530)	Bright et al. (1996)
Ontario, Canada	35–100	Azcue and Nriagu (1995)
<i>Estuarine water</i>		
<i>Baseline</i>		
Oslofjord, Norway	0.7–2.0	Abdullah et al. (1995)
Saanich Inlet, British Columbia	1.2–2.5	Peterson and Carpenter (1983)

Table 1 (continued)

Water body and location	As concentration average or range ($\mu\text{g l}^{-1}$)	Reference
Rhône Estuary, France	2.2 (1.1–3.8)	Seyler and Martin (1990)
Krka Estuary, Yugoslavia	0.13–1.8	Seyler and Martin (1991)
<i>Mining and industry influenced</i>		
Loire Estuary, France	up to 16	Seyler and Martin (1990)
Tamar Estuary, UK	2.7–8.8	Howard et al. (1988)
Schelde Estuary, Belgium	1.8–4.9	Andreae and Andreae (1989)
<i>Seawater</i>		
Deep Pacific and Atlantic	1.0–1.8	Cullen and Reimer (1989)
Coastal Malaysia	1.0 (0.7–1.8)	Yusof et al. (1994)
Coastal Spain	1.5 (0.5–3.7)	Navarro et al. (1993)
Coastal Australia	1.3 (1.1–1.6)	Maher (1985)
<i>Groundwater</i>		
Baseline UK	< 0.5–10	Edmunds et al. (1989)
As-rich provinces (e.g. Bengal Basin, Argentina, Mexico, northern China, Taiwan, Hungary)	10–5000	Das et al. (1995); BGS and DPHE (2001); Nicolli et al. (1989); Smedley et al. (2001a); Del Razo et al. (1990); Luo et al. (1997); Hsu et al. (1997); Varsányi et al. (1991)
Mining-contaminated groundwaters	50–10,000	Wilson and Hawkins (1978); Welch et al. (1988); Williams et al. (1996)
Geothermal water	< 10–50,000	Baur and Onishi (1969); White et al., (1963), Ellis and Mahon (1977)
Arsenical herbicide plant, Texas	408,000	Kuhlmeier (1997a,b)
<i>Mine drainage</i>		
Various, USA	< 1–34,000	Plumlee et al. (1999)
Iron Mountain	up to 850,000	Nordstrom and Alpers (1999)
Ural Mountains	400,000	Gelova (1977)
<i>Sediment porewater</i>		
Baseline, Swedish Estuary	1.3–166	Widerlund and Ingri (1995)
Baseline, clays, Saskatchewan, Canada	3.2–99	Yan et al. (2000)
Baseline, Amazon shelf sediments	up to 300	Sullivan and Aller (1996)
Mining-contam'd, British Columbia	50–360	Azcue et al. (1994)
Tailings impoundment, Ontario, Canada	300–100,000	McCreadie et al. (2000)
<i>Oilfield and related brine</i>		
Ellis Pool, Alberta, Canada	230	White et al. (1963)
Searles Lake brine, California	up to 243,000	White et al. (1963)

Table 2
Major As minerals occurring in nature

Mineral	Composition	Occurrence
Native arsenic	As	Hydrothermal veins
Niccolite	NiAs	Vein deposits and norites
Realgar	AsS	Vein deposits, often associated with orpiment, clays and limestones, also deposits from hot springs
Orpiment	As ₂ S ₃	Hydrothermal veins, hot springs, volcanic sublimation products
Cobaltite	CoAsS	High-temperature deposits, metamorphic rocks
Arsenopyrite	FeAsS	The most abundant As mineral, dominantly in mineral veins
Tennantite	(Cu,Fe) ₁₂ As ₄ S ₁₃	Hydrothermal veins
Enargite	Cu ₃ AsS ₄	Hydrothermal veins
Arsenolite	As ₂ O ₃	Secondary mineral formed by oxidation of arsenopyrite, native arsenic and other As minerals
Claudetite	As ₂ O ₃	Secondary mineral formed by oxidation of realgar, arsenopyrite and other As minerals
Scorodite	FeAsO ₄ ·2H ₂ O	Secondary mineral
Annabergite	(Ni,Co) ₃ (AsO ₄) ₂ ·8H ₂ O	Secondary mineral
Hoernesite	Mg ₃ (AsO ₄) ₂ ·8H ₂ O	Secondary mineral, smelter wastes
Haematolite	(Mn,Mg) ₄ Al(AsO ₄)(OH) ₈	
Conichalcite	CaCu(AsO ₄)(OH)	Secondary mineral
Pharmacosiderite	Fe ₃ (AsO ₄) ₂ (OH) ₃ ·5H ₂ O	Oxidation product of arsenopyrite and other As minerals

Table 3
Typical As concentrations in common rock-forming minerals

Mineral	As concentration range (mg kg ⁻¹)	References
<i>Sulphide minerals:</i>		
Pyrite	100–77,000	Baur and Onishi (1969); Arehart et al. (1993); Fleet and Mumin (1997)
Pyrrhotite	5–100	Boyle and Jonasson (1973); Dudas (1984); Fleet and Mumin (1997)
Marcasite	20–126,000	Dudas (1984); Fleet and Mumin (1997)
Galena	5–10,000	Baur and Onishi (1969)
Sphalerite	5–17,000	Baur and Onishi (1969)
Chalcopyrite	10–5000	Baur and Onishi (1969)
<i>Oxide minerals</i>		
Haematite	up to 160	Baur and Onishi (1969)
Fe oxide (undifferentiated)	up to 2000	Boyle and Jonasson (1973)
Fe(III) oxyhydroxide	up to 76,000	Pichler et al. (1999)
Magnetite	2.7–41	Baur and Onishi (1969)
Ilmenite	<1	Baur and Onishi (1969)
<i>Silicate minerals</i>		
Quartz	0.4–1.3	Baur and Onishi (1969)
Feldspar	<0.1–2.1	Baur and Onishi (1969)
Biotite	1.4	Baur and Onishi (1969)
Amphibole	1.1–2.3	Baur and Onishi (1969)
Olivine	0.08–0.17	Baur and Onishi (1969)
Pyroxene	0.05–0.8	Baur and Onishi (1969)
<i>Carbonate minerals</i>		
Calcite	1–8	Boyle and Jonasson (1973)
Dolomite	<3	Boyle and Jonasson (1973)
Siderite	<3	Boyle and Jonasson (1973)
<i>Sulphate minerals</i>		
Gypsum/anhydrite	<1–6	Boyle and Jonasson (1973)
Barite	<1–12	Boyle and Jonasson (1973)
Jarosite	34–1000	Boyle and Jonasson (1973)
<i>Other minerals</i>		
Apatite	<1–1000	Baur and Onishi (1969), Boyle and Jonasson (1973)
Halite	<3–30	Stewart (1963)
Fluorite	<2	Boyle and Jonasson (1973)

Table 5
Studies of As adsorption by metal oxides

Mineral	Comment	Reference
Aluminium oxides	As(V) and As(III) adsorption on activated alumina: pH dependence, kinetics, column breakthrough. Regeneration by desorbing with NaOH. Modelling with pH-dependent Langmuir isotherm (for As) and surface complexation model (for protons)	Ghosh and Yuan (1987)
'Amorphous' aluminium hydroxide	As(V) on precipitated Al(OH) ₃ (pH 3–10). 'Adsorption' exceeded 15 mol kg ⁻¹ at pH 5. Fitted data to pH dependent Langmuir isotherm	Anderson et al. (1976)
HFO	Kinetics and pH dependence of As(V) and As(III) adsorption on HFO (202 m ² g ⁻¹). Found very high As(V) and As(III) loadings (up to 4–5 mol As kg ⁻¹) at the highest concentrations. pH adsorption envelopes at various As _T loadings	Raven et al. (1998)
HFO	Adsorption isotherms for arsenite and arsenate over free concentration range from 10 ⁻⁷ to 10 ⁻³ M (pH 4–10). Fitted to Langmuir isotherm at low concentrations and linear isotherm at higher concentrations. Dzombak and Morel (1990) fitted this data to their diffuse double layer model	Pierce and Moore (1982)
HFO	Sorption of As(V) and As(III) on HFO at As concentrations of environmental significance (low micromolar range) and pH 4–9. Compared results with Dzombak and Morel (1990) model predictions—generally reasonable agreement. SO ₄ decreased adsorption of As(V) and As(III), especially at low pH, while Ca increased As(V) adsorption at high pH. 1 mM bicarbonate did not affect either As(V) or As(III) adsorption greatly	Wilkie and Hering (1996)
HFO	A wide angle X-ray scattering (and EXAFS) study of two-line ferrihydrite coprecipitated with varying amounts of As(V) suggested that the As reduced crystallite size because of the formation of strongly bound inner sphere complex between As(V) and edge sharing Fe(O,OH) ₆ octahedra. Saturation at As/Fe mol ratio of 0.68	Waychunas et al. (1996)
HFO	As(III) and As(V) adsorption and OH ⁻ release/uptake on synthetic two-line ferrihydrite. As(V) at pH 9.2 released up to 1 mol OH ⁻ per mol As sorbed whereas As(III) released < 0.25 mol As per mol Fe. At pH 4.6, OH ⁻ release was much less for As(V) adsorption and under these conditions there was a net release of H ⁺ by arsenite. These differences reflect the mechanism of As adsorption and influence the pH dependence of adsorption	Jain et al. (1999)
Granular 'ferric hydroxide' (akageneite)	As(V) isotherms given in the sub-μM concentration range; SO ₄ competition significant at mM concentrations below pH 7 only; phosphate competition at 'natural' groundwater concentrations	Driehaus et al. (1998)
Goethite	An EXAFS and XANES study of As(III) adsorption to a synthetic goethite suggested bidentate inner sphere binding. One plot of As(III) and As(V) pH adsorption envelopes. As(III) data fitted to Constant Capacitance SCM	Manning et al. (1998)
Goethite	Batch adsorption of As(V) on synthetic goethite. Used Mo blue analysis for As. Shows pH edge at about pH 9. Data fitted Langmuir isotherm presumably at constant pH (up to 60 mg l ⁻¹ As)	Matis et al. (1997)
Goethite	Successfully applied the CD-MUSIC surface complexation model to literature data for anion adsorption to goethite including As(V)-P competition. The CD-MUSIC is the most promising of the SCMs for modelling complex natural systems	Hiemstra and van Riemsdijk (1999)
Goethite	As(V) adsorption on synthetic goethite primarily for a study of impact on flocculation and electrokinetics. No isotherms. Final pH varied but not defined	Matis et al. (1999)

(continued on next page)

Table 5 (continued)

Mineral	Comment	Reference
Goethite	EXAFS study of As(V) and Cr (VI) adsorption on goethite. Monodentate binding favoured at low surface coverages of As(V), bidentate at high surface coverages	Fendorf et al. (1997)
Manganese oxides	As(III) and As(V) removal by MnO ₂ (s) is similar, up to say 5 mmol As mol ⁻¹ Mn at μM As equilibrium solution concentrations. Freundlich isotherm obeyed. As(III) oxidised to As(V). Rapid oxidation (minutes) and adsorption of As(III). Monitored Mn release and effect of pH, Ca, phosphate and sulphate	Driehaus et al. (1995)
Birnessite, cryptomelane and pyrolusite	Studied adsorption of As(III) and As(V) and kinetics of As(III) oxidation in presence of various MnO ₂ . As(III) adsorption (per unit weight of oxide): cryptomelane > birnessite > pyrolusite whereas for As(V): cryptomelane > pyrolusite > birnessite (not detectable). No isotherms given	Oscarson et al. (1983)
Goethite, hematite and lepidocrocite	Batch adsorption of As(V), As(III), MMAA and DMAA on natural minerals (coarse-grained and very low He-Ar surface area). As adsorption: generally goethite > lepidocrocite > hematite (pH 2–12, maximum often pH 5–8). At pH 7 on goethite, As(III) > MMAA > DMAA > As(V) (?). FA (up to 50 mg l ⁻¹) tended to reduce As adsorption. Gives K _d values	Bowell (1994)
Alumina, hematite, quartz and kaolin	As(V) adsorption on natural, low surface area alumina, hematite, quartz and kaolin (0.12–5 m ² g ⁻¹) at pH 3–10. Adsorption decreases with pH; alumina = kaolin > hematite > quartz. Gives K _d values and isotherms at low concentrations. Some SO ₄ ²⁻ competition especially below pH 7. FA (> 10 mg l ⁻¹) generally reduced adsorption at pH 5–7 but not above pH 7 where FA is not adsorbed	Xu et al. (1988)
Alumina	On natural alumina, adsorption was As(V) > As(III) > MMAA = DMAA (pH > 6). Maximum adsorption at pH 5 for As(V) and pH 7 for As(III). As(V) but not As(III) adsorption decreased rapidly above pH 6. Log K _d (l kg ⁻¹) at micromolar concentrations (pH 7) was 2.5–3.5 for As(V) and about 1.5 for As(III). FA decreased adsorption	Xu et al. (1991)

Appendix C – Samples obtained and laboratory test carried on each sample

Borehole #1 (10/28/0001/700) - Haldi Chhapra

Sample code	Depth (m)	As concentration (AAS)	Scanning Electron Microscopy	Soil type
10/28/001/700/S1	0	No testing		C2
10/28/001/700/S2	2	x	x	C2
10/28/001/700/S3	3.05	x	x	Silt2
10/28/001/700/S4	3.66	x	x	Silt2
10/28/001/700/S6	4.57	x	x	Silt2
10/28/001/700/S5	5.60	Derived from SEM	x	C7
10/28/001/700/S7	6.90	x	x	C7
10/28/001/700/S8	8.65	x	x	C7
10/28/001/700/S9	13.20	Derived from SEM	x	C1-S1A
10/28/001/700/S10	16.15	Derived from SEM	x	S1
10/28/001/700/S11	17.20	No testing		S7
10/28/001/700/S12	19.30	Derived from SEM	x	S1A
10/28/001/700/S13	20.42	x		S7
10/28/001/700/S14	22.56	x		S7B
10/28/001/700/S15	23.47	x		S7B
10/28/001/700/S16	24.69	x		S7B
10/28/001/700/S17	25.30	x	x	S7
10/28/001/700/S18	28.35	x	x	S7B
10/28/001/700/S19	30.80	x	x	G7B
10/28/001/700/S20	32.70	x	x	S1A
10/28/001/700/S21	34.50	x		G1
10/28/001/700/S22	37.80	x		S7
10/28/001/700/S23	39.32	x	x	G7
10/28/001/700/S24	48.77	x	x	C2

Borehole #2 (10/28/0001/900) - Rampur Diara

Sample code	Depth (m)	As/Fe (UV Spectrophotometer)	XRD and SEM	Soil type
10/28/001/900/S1b	2.44	x	x	C2
10/28/001/900/S2b	4.57	x		C2
10/28/001/900/S3b	5.49	x		C2
10/28/001/900/S5b	7.01	x		C7
10/28/001/900/S4b	8.23	No testing		C2
10/28/001/900/S6b	8.53	Derived from SEM	x	C4
10/28/001/900/S7b	9.40	x		S1
10/28/001/900/S8b	9.80	Derived from SEM	x	C1
10/28/001/900/S9b	11.80	x		C1
10/28/001/900/S10b	14.33	Derived from SEM	x	S1A
10/28/001/900/S11b	17.40	x		S1A
10/28/001/900/S12b	19.81	No testing		S7
10/28/001/900/S13b	20.73	x		S7
10/28/001/900/S14b	23.43	x		S1A
10/28/001/900/S15b	25.10	No testing		G7b
10/28/001/900/S16b	28.15	x		G7B
10/28/001/900/S17b	29.10	Derived from SEM	x	S7
10/28/001/900/S18b	31.60	x		S1A
10/28/001/900/S19b	35	No testing		S1
10/28/001/900/S20b	37.60	x		S7
10/28/001/900/S21b	39.90	x		S7
10/28/001/900/S22b	42.90	x		S7B
10/28/001/900/S23b	46	Derived from SEM	x	Pleistocene

Borehole #3 - 10/28/0001/040 Hathitola Primary School

Sample code	Depth (m)	As/Fe (UV Spectrophotometer)	XRD and SEM	Soil type
10/28/001/040/S1c	2.30	x		C7
10/28/001/040/S2c	3.80	x		C7
10/28/001/040/S3c	5	Derived from SEM	x	C1
10/28/001/040/S4c	6.10	Derived from SEM	x	C1
10/28/001/040/S5c	9.60	x		C1
10/28/001/040/S6c	10.37	Derived from SEM	x	C4
10/28/001/040/S7c	11.30	x		C4
10/28/001/040/S8c	14.30	x		S1
10/28/001/040/S9c	16.30	x		C1
10/28/001/040/S10c	18.15	x		S7B
10/28/001/040/S11c	21.12	No testing		G7B
10/28/001/040/S12c	23.10	x		S7
10/28/001/040/S13c	23.85	x		S7
10/28/001/040/S14c	24.80	x		G7
10/28/001/040/S15c	27.60	x		S1
10/28/001/040/S16c	29.13	x		S1
10/28/001/040/S17c	31.20	x		G1
10/28/001/040/S18c	32.63	x		S1A
10/28/001/040/S19c	34.60	Derived from SEM	x	S2
10/28/001/040/S20c	34.92	x		S2
10/28/001/040/S21c	35.60	x		G7
10/28/001/040/S22c	36.52	No testing		G7
10/28/001/040/S23c	38.90	x		S7
10/28/001/040/S24c	41.18	No testing		G7
10/28/001/040/S25c	44.38	x		S1
10/28/001/040/S26c	46.20	Derived from SEM	x	Pleistocene

Appendix D - Arsenic database for boreholes in Maner block

	Number	%
>50 ppb	43	18,70
10-50 ppb	57	24,78
<10 ppb	130	56,52
Total	230	

Water Source ID	Name of Village	ARSENIC LEVEL [in ppb.]	Latitude	Longitude	Depth (m)	Altitude (m)
01/001/0406/04/NPR	Hathitola [Haldi chapra]	30			0	0
01/002/0406/04/NPR	Hathitola [Haldi chapra]	35			0	0
01/003/0406/04/NPR	Hathitola [Haldi chapra]	BDL	25,66513	84,874483	42	44,4
01/004/0406/04/NPR	Hathitola [Haldi chapra]	34	25,66527	84,87585	37,5	45,3
01/011/0406/04/NPR	Hathitola [Haldi chapra]	90			0	0
01/012/0406/04/NPR	Hathitola [Haldi chapra]	54			0	0
01/015/0406/04/NPR	Hathitola [Haldi chapra]	92			0	0
01/016/0406/04/NPR	Hathitola [Haldi chapra]	30			0	0
01/017/0406/04/NPR	Hathitola [Haldi chapra]	81			0	0
01/020/0406/04/NPR	Hathitola [Haldi chapra]	85			0	0
01/023/0406/04/NPR	Hathitola [Haldi chapra]	40			0	0
01/024/0406/04/NPR	Hathitola [Haldi chapra]	142	25,66465	84,875467	31,5	39
01/025/0406/04/NPR	Hathitola [Haldi chapra]	86			0	0
01/026/0406/04/NPR	Hathitola [Haldi chapra]	50			0	0
01/029/0406/04/NPR	Hathitola [Haldi chapra]	50			0	0
01/031/0406/04/NPR	Hathitola [Haldi chapra]	87			0	0
01/032/0406/04/NPR	Hathitola [Haldi chapra]	87			0	0
01/034/0406/04/NPR	Hathitola [Haldi chapra]	30			0	0
01/035/0406/04/NPR	Hathitola [Haldi chapra]	60			0	0
01/036/0406/04/NPR	Hathitola [Haldi chapra]	30			0	0
01/038/0406/04/NPR	Hathitola [Haldi chapra]	78	25 39.903	84 52.459	40,5	41,1
01/039/0406/04/NPR	Hathitola [Haldi chapra]	12			0	0
01/041/0406/04/NPR	Hathitola [Haldi chapra]	49			0	0
01/001/0506/04/NPR	Ramnagar	35			0	0
01/002/0506/04/NPR	Ramnagar	238	25,682	84,87945	30	50,4
01/003/0506/04/NPR	Ramnagar	201			0	0
01/004/0506/04/NPR	Ramnagar	10			0	0
01/005/0506/04/NPR	Ramnagar	10			0	0
01/006/0506/04/NPR	Ramnagar	40			0	0
01/007/0506/04/NPR	Ramnagar	171	25,66495	84,87555	39	45,6
01/081/0506/04/NPR	Ramnagar	224			0	0
01/009/0506/04/NPR	Ramnagar	145			0	0
01/010/0506/04/NPR	Ramnagar	156			0	0
01/011/0506/04/NPR	Ramnagar	88			0	0
01/012/0506/04/NPR	Ramnagar	260			0	0

01/013/0506/04/NPR	Ramnagar	99			0	0
01/004/0506/04/NPR	Ramnagar	250			0	0
01/018/0506/04/NPR	Ramnagar	112			0	0
10/28/0001/093/42	Ramnagar	0			0	0
10/28/0001/093/43	Ramnagar	0			0	0
10/28/0001/093/44	Ramnagar	0			0	0
10/28/0001/093/45	Ramnagar	0			0	0
01/018/0506/04/NPR	Badantolla	112	25 40.417	84 52.586	0	60
01/019/0506/04/NPR	Badantolla	10			0	0
01/021/0506/04/NPR	Badantolla	55	25 40.860	84 52.517	25,5	44,7
01/023/0506/04/NPR	Badantolla	169	25 40.857	84 52.501	35,4	42,6
01/024/0506/04/NPR	Badantolla	52	25 40.869	84 52.569	0	41,4
01/025/0506/04/NPR	Badantolla	296			0	0
01/026/0506/04/NPR	Badantolla	151	25 40.944	84 52.479	34,8	41,7
01/027/0506/04/NPR	Badantolla	92	25 40.956	84 52.571	39	40,5
01/029/0506/04/NPR	Badantolla	0,5			0	0
01/030/0506/04/NPR	Badantolla	0			0	0
01/01/0906/04/NPR	Naikatola	25			0	0
01/02/0906/04/NPR	Naikatola	196			0	0
01/03/0906/04/NPR	Naikatola	71			0	0
01/05/0906/04/NPR	Naikatola	105			0	0
01/06/0906/04/NPR	Naikatola	60			0	0
01/07/0906/04/NPR	Naikatola	20			0	0
01/10/0906/04/NPR	Naikatola	110			0	0
01/11/0906/04/NPR	Naikatola	106			0	0
01/12/0906/04/NPR	Naikatola	20			0	0
01/15/0906/04/NPR	Naikatola	62			0	0
01/16/0906/04/NPR	Naikatola	10			0	0
01/17/0906/04/NPR	Naikatola	29	25 41.045	84 52.275	31,8	41,4
01/18/0906/04/NPR	Naikatola	143			0	0
01/19/0906/04/NPR	Naikatola	10			0	0
01/20/0906/04/NPR	Naikatola	30			0	0
01/21/0906/04/NPR	Naikatola	131	25 41.114	84 52.359	24	44,7
01/22/0906/04/NPR	Naikatola	110			0	0
01/23/0906/04/NPR	Naikatola	125	25 41.043	84 52.283	25,5	43,2
01/24/0906/04/NPR	Naikatola	110	25 40.995	84 52.290	18	43,8
01/25/0906/04/NPR	Naikatola	81	25 41.005	84 52.288	24	44,4
01/28/0906/04/NPR	Naikatola	185	25 41.117	84 52.389	31,5	42,6
01/29/0906/04/NPR	Naikatola	221			0	0
01/30/0906/04/NPR	Naikatola	125			0	0
01/31/0906/04/NPR	Naikatola	130	25 41.021	84 52.301	33	43,2
01/32/0906/04/NPR	Naikatola	205			0	0
01/33/0906/04/NPR	Naikatola	95			0	0
01/34/0906/04/NPR	Naikatola	22			0	0
01/35/0906/04/NPR	Naikatola	92			0	0
01/36/0906/04/NPR	Naikatola	75			0	0
01/37/0906/04/NPR	Naikatola	66	25 41.075	84 52.340	30	41,4

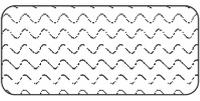
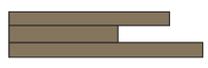
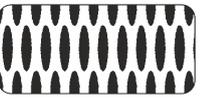
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01/002/1006/04/NPR	Puranka tola	90			0	0
01/003/1006/04/NPR	Puranka tola	190	25 40.990	84 52.195	0	63,6
01/004/1006/04/NPR	Puranka tola	110			0	0
01/005/1006/04/NPR	Puranka tola	0			0	0
01/007/1006/04/NPR	Puranka tola	181			0	0
01/008/1006/04/NPR	Puranka tola	110			0	0
01/009/1006/04/NPR	Puranka tola	238	25 40.894	84 52.178	31,5	48
01/010/1006/04/NPR	Puranka tola	90	25 40.908	84 52.181	0	48
01/011/1006/04/NPR	Puranka tola	170	25 40.909	84 52.196	35,7	49,2
01/012/1006/04/NPR	Puranka tola	114			0	0
01/013/1006/04/NPR	Puranka tola	116	25 40.953	84 52.213	30	57,6
01/014/1006/04/NPR	Puranka tola	110			0	0
01/015/1006/04/NPR	Puranka tola	297			0	0
01/016/1006/04/NPR	Puranka tola	275	25 40.938	84 52.180	33	51
01/017/1006/04/NPR	Puranka tola	323			0	0
01/018/1006/04/NPR	Puranka tola	100	25 40.970	84 52.211	30	61,8
01/019/1006/04/NPR	Puranka tola	30			0	0
01/020/1006/04/NPR	Puranka tola	119	25 41.004	84 52.161	35,1	41,4
01/021/1006/04/NPR	Puranka tola	68	25 40.974	84 52.200	39	61,8
01/022/1006/04/NPR	Puranka tola	110			0	0
01/023/1006/04/NPR	Puranka tola	143	25 41.016	84 52.188	36,6	43,8
01/024/1006/04/NPR	Puranka tola	84	25 41.021	84 52.171	30	44,1
01/025/1006/04/NPR	Puranka tola	84	25 41.027	84 52.172	30	41,4
01/026/1006/04/NPR	Puranka tola	94	25 41.018	84 52.233	31,5	71,4
01/027/1006/04/NPR	Puranka tola	75			0	0
01/028/1006/04/NPR	Puranka tola	90			0	0
01/031/1006/04/NPR	Puranka tola	55	25 40.948	84 52.204	37,5	53,1
01/034/1006/04/NPR	Puranka tola	53	25 40.979	84 52.203	31,5	58,8
01/001/1206/04/NPR	Satannua	112	25 40.776	84 52.390	35,1	37,8
01/002/1206/04/NPR	Satannua	340			0	0
01/003/1206/04/NPR	Satannua	30			0	0
01/004/1206/04/NPR	Satannua	91			0	0
01/005/1206/04/NPR	Satannua	79	25 40.747	84 52.385	30	40,2
01/006/1206/04/NPR	Satannua	140			0	0
01/007/1206/04/NPR	Satannua	20			0	0
01/008/1206/04/NPR	Satannua	25	25 40.698	84 52.390	48	31,2
01/011/1206/04/NPR	Satannua	124	25 40.755	84 52.434	0	39
01/012/1206/04/NPR	Satannua	115			0	0
01/013/1206/04/NPR	Satannua	62	25 40.610	84 52.271	40,5	43,5
01/014/1206/04/NPR	Satannua	120	25 40.491	84 52.372	27	43,2
01/015/1206/04/NPR	Satannua	115			0	0
01/016/1206/04/NPR	Satannua	50			0	0
01/018/1206/04/NPR	Satannua	90	25 40.763	84 52.432	30	35,7
01/019/1206/04/NPR	Satannua	128			0	0

01/020/1206/04/NPR	Satannua	49	25 40.659	84 52.366	34,5	30,3
01/021/1206/04/NPR	Satannua	278	25 40.749	84 52.323	33	44,7
01/022/1206/04/NPR	Satannua	110			0	0
01/024/1206/04/NPR	Satannua	150			0	0
01/025/1206/04/NPR	Satannua	110			0	0
01/026/1206/04/NPR	Satannua	110			0	0
01/027/1206/04/NPR	Satannua	52	25 40.780	84 52.366	27	40,2
01/028/1206/04/NPR	Satannua	101	25 40.723	84 52.375	30	32,7
01/029/1206/04/NPR	Satannua	191	25 40.546	84 52.382	31,5	42,6
01/030/1206/04/NPR	Satannua	223			0	0
01/031/1206/04/NPR	Satannua	66			0	0
01/032/1206/04/NPR	Satannua	213			0	0
01/033/1206/04/NPR	Satannua	55	25 40.756	84 52.433	30	36,9
01/034/1206/04/NPR	Satannua	253	25 40.736	84 52.340	21	44,7
01/035/1206/04/NPR	Satannua	47	25 40.756	84 52.434	0	35,7
01/036/1206/04/NPR	Satannua	47			0	0
01/037/1206/04/NPR	Satannua	57			0	0
01/038/1206/04/NPR	Satannua	59			0	0
01/039/1206/04/NPR	Satannua	40			0	0
01/040/1206/04/NPR	Satannua	0			0	0
01/015/2206/04/NPR	Dudhaila	129			0	0
01/016/2206/04/NPR	Dudhaila	141			0	0
01/017/2206/04/NPR	Dudhaila	95	25 40.449	84 52.578	33	63,3
01/018/2206/04/NPR	Dudhaila	35	25 40.490	84 52.580	33	39,3
01/019/2206/04/NPR	Dudhaila	170	25 40.491	84 52.610	33	36,3
01/020/2206/04/NPR	Dudhaila	109	25 40.495	84 52.630	0	39,3
01/021/2206/04/NPR	Dudhaila	84	25 40.520	84 52.680	33	39,3
01/023/2206/04/NPR	Dudhaila	67	25 40.506	84 52.704	0	38,1
01/024/2206/04/NPR	Dudhaila	76	25 40.510	84 52.689	36	41,4
01/025/2206/04/NPR	Dudhaila	87	25 40.518	84 52.743	27	39,3
01/027/2206/04/NPR	Dudhaila	127	25 40.519	84 52.771	25,5	37,2
01/028/2206/04/NPR	Dudhaila	127	25 40.530	84 52.773	31,5	36,3
01/029/2206/04/NPR	Dudhaila	117	25 40.507	84 52.788	28,5	37,8
01/030/2206/04/NPR	Dudhaila	88	25 40.552	84 52.911	0	36,9
01/033/2206/04/NPR	Dudhaila	92	25 40.870	84 52.567	31,5	41,7
10/28/0001/109/01	Bhawanitola	50	25 39.988	84 50.748	45	38,1
10/28/0001/109/02	Bhawanitola	60			0	0
10/28/0001/109/03	Bhawanitola	40			0	0
10/28/0001/109/04	Bhawanitola	60			0	0
10/28/0001/109/05	Bhawanitola	30			0	0
10/28/0001/109/06	Bhawanitola	0			0	0
10/28/0001/109/07	Bhawanitola	70	25 40.067	84 50.865	25,5	35,4
10/28/0001/109/08	Bhawanitola	50			0	0
10/28/0001/109/09	Bhawanitola	0			0	0
10/28/0001/109/10	Bhawanitola	0	25 40.139	84 50.858	0	43,8
10/28/0001/109/11	Bhawanitola	0	25 40.136	84 50.842	25,5	44,1
10/28/0001/109/12	Bhawanitola	0			0	0

10/28/0001/109/13	Bhawanitola	0	25 40.138	84 50.816	30	45
10/28/0001/109/14	Bhawanitola	50			0	0
10/28/0001/109/15	Bhawanitola	0			0	0
10/28/0001/109/16	Bhawanitola	10	25 40.113	84 50.807	30	42,9
10/28/0001/109/17	Bhawanitola	0	25 40.103	84 50.814	24	43,5
10/28/0001/109/18	Bhawanitola	30	25 40.122	84 50.797	27	45,9
10/28/0001/109/19	Bhawanitola	30			0	0
10/28/0001/109/20	Bhawanitola	10			0	0
10/28/0001/109/21	Bhawanitola	60			0	0
10/28/0001/109/22	Bhawanitola	40	25 40.084	84 50.879	25,5	52,8
10/28/0001/109/23	Bhawanitola	50	25 40.085	84 50.887	0	40,2
10/28/0001/109/24	Bhawanitola	20			0	0
10/28/0001/109/25	Bhawanitola	50			0	0
10/28/0001/109/26	Bhawanitola	40			0	0
10/28/0001/109/27	Bhawanitola	0	25 40.012	84 50.738	33	35,1
10/28/0001/109/28	Bhawanitola	40	25 40.001	84 50.814	0	39
10/28/0001/109/29	Bhawanitola	60	25 39.969	84 50.828	0	41,4
10/28/0001/109/30	Bhawanitola	40	25 39.974	84 50.822	27	40,2
10/28/0001/109/31	Bhawanitola	40	25 40.244	84 50.832	33	41,4
10/28/0001/109/32	Bhawanitola	0	25 39.960	84 50.859	24	41,1
10/28/0001/109/33	Bhawanitola	30	25 39.974	84 50.819	27	39,6
10/28/0001/109/34	Bhawanitola	40			0	0
10/28/0001/109/01	Rampur Diara	40			0	0
10/28/0001/109/02	Rampur Diara	0	25 39.823	84 50.775	60	36,3
10/28/0001/109/03	Rampur Diara	50			0	0
10/28/0001/109/04	Rampur Diara	60	25 39.782	84 50.712	19,8	49,2
10/28/0001/109/05	Rampur Diara	60	25 39.742	84 50.696	21	38,7
10/28/0001/109/06	Rampur Diara	60	25 39.708	84 50.560	24	39,3
10/28/0001/109/07	Rampur Diara	30			0	0
10/28/0001/109/09	Rampur Diara	40			0	0
10/28/0001/109/10	Rampur Diara	50	25 39.671	84 50.544	33	38,4
10/28/0001/109/11	Rampur Diara	40	25 39.687	84 50.547	33	39,3
10/28/0001/109/12	Rampur Diara	30			0	0
10/28/0001/109/13	Rampur Diara	0			0	0
10/28/0001/109/14	Rampur Diara	0			0	0
10/28/0001/109/15	Rampur Diara	10	25 39.895	84 50.511	27	34,5
10/28/0001/109/16	Rampur Diara	0	25 39.965	84 50.595	28,5	32,7
10/28/0001/109/17	Rampur Diara	0	25 39.890	84 50.594	25,5	36
10/28/0001/109/18	Rampur Diara	0			0	0
10/28/0001/109/19	Rampur Diara	30			0	0
10/28/0001/109/20	Rampur Diara	0			0	0
10/28/0001/109/21	Rampur Diara	0	25 39.884	84 50.523	36	36,3
10/28/0001/109/22	Rampur Diara	110	25 40.216	84 50.321	24	39
10/28/0001/109/23	Rampur Diara	40			0	0
10/28/0001/109/26	Rampur Diara	30			0	0
10/28/0001/109/30	Rampur Diara	0			0	0
10/28/0001/109/31	Rampur Diara	30			0	0

10/28/0001/109/32	Rampur Diara	0			0	0
10/28/0001/109/33	Rampur Diara	0			0	0
10/28/0001/109/35	Rampur Diara	0			0	0
10/28/0001/109/37	Rampur Diara	0			0	0
10/28/0001/109/38	Rampur Diara	30			0	0
10/28/0001/109/39	Rampur Diara	0			0	0
10/28/0001/109/40	Rampur Diara	0			0	0
Above Water Source IDs are based on Ward Map Village Codes as per initial Protoc					0	0

LEGEND

	C1	CLAY		PLANT ROOTS
	C2			BURROWS
	C4			
		SILT		PARALLEL LAMINATION
		SAND		WAVY LAMINATION
	S1			TROUGH CROSS BEDDING
	S1A			
	S7			HETEROLITHIC BEDDING
	S7B			HETEROLITHIC WAVY BEDDING
	S2			
		GRAVEL		HOMOGENOUS
				INDICATION OF SEQUENCE

Appendix E – Borehole #1

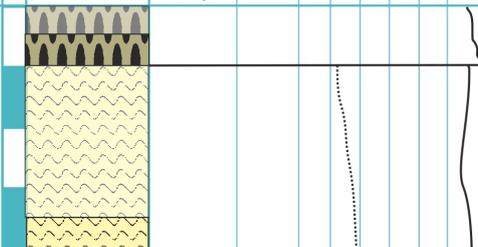
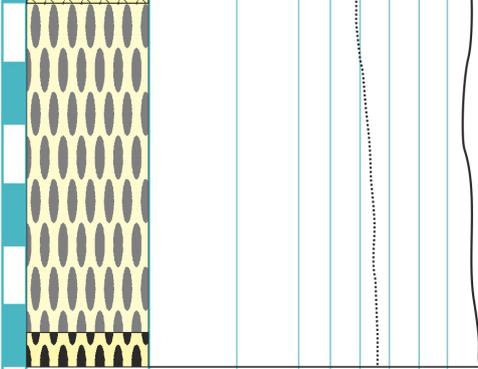
18-09-20 to 22-09-10 Borehole #1 (10/28/0001/700) Location: Haldi Chhapra (Maner District) - page 1

Stratigraphic units	Photo	Samples	Depth m	Macroscopic description										Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content	
				Columnar section										Arsenic (µg/mg)	Mineralogy			
				Composition & Texture	Grain size								Gravel					
Clay	Silt	vf	f		m	c	vc											
				Very fine, dark brown soil.													First 0.62 m were excavated before drilling to set the drilling equipment (bamboo structure)	
		S1															Brown sand and clay layer intercalations. Quartz and clay minerals. Quartz and muscovite rich. Organic matter and carbon nodules are present.	
		S2	1.52												0.27	Quartz, calcite and clay minerals. Fe coatings on quartz grains. Al and Ca rich.		
		S3	3.05														Fine pale sample, solute in water (probably high percentage of silt).	
		S4													0.42			
		S6	4.57														Carbon nodules (0.5 cm) + oxidized stains	
		S5													0.52	Ilmenite biotite muscovite Fe rich		
		S7	6.10														Highly bioturbated	
															0.57	Carbon present in stains and nodules		
			7.62														Transitional layer	

18-09-20 to 22-09-10 Borehole #1 (10/28/0001/700) Location: Haldi Chhapra (Maner District) - page 4																				
Stratigraphic units	Photo	Samples	Depth m	Macroscopic description								Structures			Additional Description [strike, dip, bed thickness, colour]	Fossil content				
				Columnar section				Grain size				Transport direction	Sedimentary/Diagenetic structures	Bio-turb.						
				Composition & Texture	Clay	Silt	vf	f	m	c	vc						Gravel			
		S15															0.33	(All layers were sampled as rubble)		
			24.38															0.32	Quartz and plagioclase rich sand, yellow to brownish oxidised appearance. High calcareous content.	
		S16																0.47	Approximately 50% to 70% of SiO2 minerals	
			25.91																	
		S17																		
			27.43																	
			28.96																	
		S18																		
			30.48																	

18-09-20 to 22-09-10 Borehole #1 (10/28/0001/700) Location: Haldi Chhapra (Maner District) - page 5																
Stratigraphic units	Photo	Samples	Depth m	Macroscopic description							Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content		
				Columnar section				Grain size			Gravel	Arsenic (µg/mg)			Mineralogy	
				Composition & Texture	Clay	Silt	vf	f	m	c						vc
		S19										0.12		(All samples were obtained as rubble)		
		S20	32.00											Quartz calcite feldspar very small percentage of kaolinite	High silica minerals content - gravel of 0.3 cm app.	
		S21	33.53										0.22			
			35.05													
			36.58												Noticeable increase in oxidized material	
		S22	38.10										0.30		Mica-rich material	Relative increase in K-feldspars

18-09-20 to 22-09-10 Borehole #1 (10/28/0001/700) Location: Haldi Chhapra (Maner District) - page 6

Stratigraphic units	Photo	Samples	Depth m	Macroscopic description										Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content		
				Columnar section										Grain size				Arsenic (µg/mg)	Mineralogy
				Composition & Texture	Clay	Silt	vf	f	m	c	vc	Gravel	Gravel						
		S23	39.62											0.09		0.2-0.4 cm			
		S24	48.77											0.30		The extrapolated gravel layer is not very accurate, due to lack of data obtained while drilling.			
END OF BOREHOLE																			

Appendix F – Borehole #2

26-09-10 to 01-10-10 Borehole #2 (10/28/0001/900) Rampur Diara (Highschool) - Page 1														
Stratigraphic units	Photo	Samples	Depth m	Macroscopic description							Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content
				Columnar section							Arsenic (µg/mg)	Mineralogy		
				Composition & Texture	Grain size									
Clay	Silt	vf	f	m	c	vc								
			1.52										Light colored soil	
		S1b	3.05								0.52		(Very slurry sample mixed with lubricant. Blonde silty-sandy soil, high bioturbation. Similar to the first layers that were sampled below it.)	
		S2b	4.57								0.20	Quartz Kaolinite Calcite Possibly Fe-coated	Brown sand, quartz and feldspar rich contains a high percentage of mica and mafic minerals. Mostly subangular.	
		S3b	6.10								0.17	Biotite Ilmenite Quartz grain with Fe coating	Less brownish sand, also rich in mica and mafic minerals.	
		S5b	7.62								0.32	Feldspar Ilmenite Biotite	Contains carbon nodules	

26-09-10 to 01-10-10 Borehole #2 (10/28/0001/900) Rampur Diara (Highschool) - Page 2

Stratigraphic units	Photo	Samples	Depth m	Macroscopic description											Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content			
				Columnar section											Arsenic (µg/mg)	Mineralogy					
				Composition & Texture	Grain size								Gravel								
Clay	Silt	vf	f	m	c	vc															
		S4b																Quartz grain and clay particles with Fe coating	Unoxidized clay. Contains layers of leaves and organic material. Wavy lamination, slightly more oxidized, of yellow-brownish color.		
		S6b															Biotite calcite kaolinite				
			7.62														0.18		High organic content. Discolored off-white stains.		
		S7b																			
		S8b																			
			9.14																	Clayey silt. Contains wavy lamination of vfs.	
		S9b																			
			10.67														0.69			Very dark gray sand layer, mixed with silt.	
			12.19																		
		S10b																Biotite Ilmenite muscovite possibly small amount of feldspars			
			13.72																		

26-09-10 to 01-10-10 Borehole #2 (10/28/0001/900) Rampur Diara (Highschool) - Page 3														
Stratigraphic units	Photo	Samples	Depth m	Macroscopic description							Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content
				Columnar section							Arsenic (µg/mg)	Mineralogy		
				Composition & Texture	Clay	Silt	vf	f	m	c				
		S11b	16.76									0.36		
		S12b	18.29											Subrounded, but contains purple mineral grains that are coarser and angular
		S13b	19.81											
			21.34									0.15		"Salt and pepper" appearance
			22.86											Contains some K-fsp and light green angular mineral grains

26-09-10 to 01-10-10 Borehole #2 (10/28/0001/900) Rampur Diara (Highschool) - Page 4

Macroscopic description															
Stratigraphic units	Photo	Samples	Depth m	Columnar section							Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content	
				Composition & Texture	Grain size						Gravel	Arsenic (µg/mg)			Mineralogy
					Clay	Silt	vf	f	m	c					
		S14b									0.14	Mica rich (Biotite and muscovite)			
			24.38												
		S15b											Green gravels, subangular of 0.7 to 1 cm diameter in smaller diameter gravel.		
			25.91										0.3-0.6 cm		
													Particles of maximum 2 cm diameter in smaller diameter gravel		
			27.43												
		S16b									0.10	Quartz calcite clay particles with Fe coating	~ 0.3 cm		
			28.96												
		S17b													
			30.48										0.2-0.4 cm		

26-09-10 to 01-10-10 Borehole #2 (10/28/0001/900) Rampur Diara (Highschool) - Page 5															
Stratigraphic units	Photo	Samples	Depth m	Macroscopic description							Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content	
				Columnar section											
				Composition & Texture	Grain size						Gravel	Arsenic (µg/mg)			Mineralogy
Clay	Silt	vf	f		m	c	vc								
		S18b	32.00									0.26			
			33.53										0.2 to 0.4 cm	CaCO ₃ - rich	
		S19b	35.05										Fe and V coating on Quartz grain. Possible presence of Schreyerite	CaCO ₃ - rich	
			36.58										High mica percentage	CaCO ₃ - rich	
		S20b	38.10									0.32	0.2-0.5 cm		

26-09-10 to 01-10-10 Borehole #2 (10/28/0001/900) Rampur Diara (Highschool) - Page 6

Macroscopic description															
Stratigraphic units	Photo	Samples	Depth m	Columnar section							Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content	
				Composition & Texture	Grain size						Gravel	Arsenic (µg/mg)			Mineralogy
					Clay	Silt	vf	f	m	c					
		S21b	39.62									0.26		Relatively high mica content	
			48.77											More angular	
		S22b	57.92									0.09	Feldspar with non ferrous coating		
			67.07												
			76.22											Relatively high quartz and mica content	

Appendix G – Borehole #3

07-10-10 to 09-10-10 Borehole #3 (10/28/0001/040) Hathitola (Primary School) - Page 2

Stratigraphic units	Photo	Samples	Depth m	Macroscopic description											Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content	
				Columnar section											Arsenic (µg/mg)	Mineralogy			
				Composition & Texture	Grain size								Gravel						
				Clay	Silt	vf	f	m	c	vc									
			7.62																
		S5c													0.69				Yellow fine sand intercalated with clay
		S6c	9.14																More homogeneous layers Black sand intercalated with clay. Very high organic content and carbon.
		S7c													1.11	Feldspar (orthoclase)		Organic matter and carbon-rich layers	
			10.67																
		S8c	12.19																
			13.72																
															0.37				

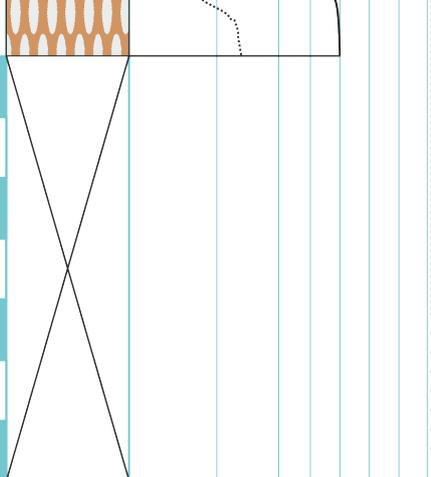
07-10-10 to 09-10-10 Borehole #3 (10/28/0001/040) Hathitola (Primary School) - Page 3															
Stratigraphic units	Photo	Samples	Depth m	Macroscopic description							Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content	
				Columnar section							Arsenic (µg/mg)	Mineralogy			
				Composition & Texture	Grain size										Gravel
Clay	Silt	vf	f	m	c	vc	Gravel								
		S9c	16.76									1.30	Clay particles with Fe coating	Clayey sand. The clayey part is lighter gray than the above layers.	
		S10c	18.29									0.36			
		S11c	21.34												
			22.86												0.5 - 1 cm

Drilling was paused and the pipes were pulled out.

07-10-10 to 09-10-10 Borehole #3 (10/28/0001/040) Hathitola (Primary School) - Page 4

Stratigraphic units	Photo	Samples	Depth m	Macroscopic description								Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content
				Columnar section								Arsenic (µg/mg)	Mineralogy		
				Composition & Texture	Grain size										
Clay	Silt	vf	f	m	c	vc	Gravel								
		S12c										0.15			
		S13c										0.11			
			24.38											0.2 - 0.4 cm	
		S14c										0.32		K-feldspar rich	
		S15c	25.91									0.25			
			27.43												
		S16c	28.96									0.27			
			30.48											0.2-1 cm	

07-10-10 to 09-10-10 Borehole #3 (10/28/0001/040) Hathitola (Primary School) - Page 5														
Stratigraphic units	Photo	Samples	Depth m	Macroscopic description							Laboratory results		Additional Description [strike, dip, bed thickness, colour]	Fossil content
				Columnar section							Arsenic (µg/mg)	Mineralogy		
				Composition & Texture	Grain size									
Clay	Silt	vf	f	m	c	vc	Gravel							
		S17c									0.32		Relatively higher content of K-feldspar	
		S18c	32.00								0.15	Biotite ilmenite muscovite small amount of feldspars		
			33.53										Muscovite in vary large particles.	
		S19c												
		S20c	35.05								0.36			
		S21c									0.46		0.2 to 3 cm CaCO rich	
		S22c	36.58										Yellow-pinkish appearance	
			38.10										0.2-0.7 cm	

07-10-10 to 09-10-10 Borehole #3 (10/28/0001/040) Hathitola (Primary School) - Page 7														
Stratigraphic units	Photo	Samples	Depth m	Macroscopic description							Laboratory results	Additional Description [strike, dip, bed thickness, colour]	Fossil content	
				Columnar section										
				Composition & Texture	Grain size									Gravel
Clay	Silt	vf	f		m	c	vc							
		S26c	85.27									Calcite and kaolinite	Calcareous concretions in light brown sand. Contains some amount of off-white to pale gray clay. Possibly Pleistocene formation.	
END OF BOREHOLE														

Testing specifications for SEM and XRD
21-10-2010

Chemical elements to be tested in SEM:

Most important: As, Fe, C, O, OH, Mg

Others: Mn, Ca, Na, Si, Al, K, F, Cu

Especially for sample S6b: All the above plus Ti

Geothermal gradient gives an increase of 0 to 1.5 °C, which can be neglected when testing.

XRD testing

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na, Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals	General formula: AlSi ₃ O ₄
- Illite (K, H ₃ O)(Al, Mg, Fe) ₂ (Si, Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)]	
- Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄	
- Smectite (Na, Ca) _{0.33} (Al, Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	
Hornblende	Ca ₂ (Mg, Fe, Al) ₅ (Al, Si) ₈ O ₂₂ (OH) ₂
Serpentine	(Mg, Fe) ₃ Si ₂ O ₅ (OH) ₄
Garnet (Ferrous garnet expected mostly)	X ²⁺ ₃ Y ³⁺ ₂ Si ₃ O ₁₂ X stands for Ca, Fe ²⁺ , Mn, and Mg Y stands for Al, Cr, and Fe ³⁺
Olivine -Fayalite (Fe ₂ SiO ₄) -Forsterite (Mg ₂ SiO ₄)	XSiO ₄ X is Ca, Mn, Mg or Fe (most common is Mg OR Fe)
Pyroxene group	XY(Si, Al) ₂ O ₆ X stands for Ca, Na, Fe ²⁺ , Mg Y stands for Cr, Al, Mg, Mn, Fe ³⁺
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (As ₂ S) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample S5

Expected mineralogical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase (higher percentage than K-fespar)	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample S9

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Pyroxene group	XY(Si,Al) ₂ O ₆ X stands for Ca, Na, Fe ⁺² , Mg Y stands for Cr, Al, Mg, Mn, Fe ⁺³
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample S10

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O) - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Hornblende	Ca ₂ (Mg, Fe, Al) ₅ (Al, Si) ₈ O ₂₂ (OH) ₂
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample S12

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar (higher in percentage)	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O) - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Hornblende	Ca ₂ (Mg, Fe, Al) ₅ (Al, Si) ₈ O ₂₂ (OH) ₂
Pyroxene group	XY(Si,Al) ₂ O ₆ X stands for Ca, Na, Fe ⁺² , Mg Y stands for Cr, Al, Mg, Mn, Fe ⁺³
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample S20

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Hornblende	Ca ₂ (Mg, Fe, Al) ₅ (Al, Si) ₈ O ₂₂ (OH) ₂
Serpentine	(Mg,Fe) ₃ Si ₂ O ₅ (OH) ₄
Garnet (Ferrous garnet expected mostly)	X ²⁺ ₃ Y ³⁺ ₂ Si ₃ O ₁₂ X stands for Ca, Fe ²⁺ , Mn, and Mg Y stands for Al, Cr, and Fe ³⁺
Olivine -Fayalite (Fe ₂ SiO ₄) -Forsterite (Mg ₂ SiO ₄)	XSiO ₄ X stands for Ca, Mn, Mg or Fe (most common is Mg OR Fe)
Pyroxene group	XY(Si,Al) ₂ O ₆ X stands for Ca, Na, Fe ²⁺ , Mg Y stands for Cr, Al, Mg, Mn, Fe ³⁺
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample S6b

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na, Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Pyroxene group	XY(Si,Al) ₂ O ₆ X stands for Ca, Na, Fe ⁺² , Mg Y stands for Cr, Al, Mg, Mn, Fe ⁺³
Clay minerals - Illite (K, H ₃ O)(Al, Mg, Fe) ₂ (Si, Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na, Ca) _{0.33} (Al, Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample 8b

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na, Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Pyroxene group	XY(Si,Al) ₂ O ₆ X stands for Ca, Na, Fe ⁺² , Mg Y stands for Cr, Al, Mg, Mn, Fe ⁺³
Clay minerals - Illite (K, H ₃ O)(Al, Mg, Fe) ₂ (Si, Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na, Ca) _{0.33} (Al, Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃)	Minerals containing As in various forms.

Sample 10b

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Hornblende	Ca ₂ (Mg, Fe, Al) ₅ (Al, Si) ₈ O ₂₂ (OH) ₂
Garnet (Ferrous garnet expected mostly)	X ²⁺ ₃ Y ³⁺ ₂ Si ₃ O ₁₂ X stands for Ca, Fe ²⁺ , Mn, and Mg Y stands for Al, Cr, and Fe ³⁺
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample 17b

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Hornblende	Ca ₂ (Mg, Fe, Al) ₅ (Al, Si) ₈ O ₂₂ (OH) ₂
Garnet (Ferrous garnet expected mostly)	X ²⁺ ₃ Y ³⁺ ₂ Si ₃ O ₁₂ X stands for Ca, Fe ²⁺ , Mn, and Mg Y stands for Al, Cr, and Fe ³⁺
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample 23b

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS)	Minerals containing As in various forms.

Sample S3c

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample S4c

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample S6c

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Pyroxene group	XY(Si,Al) ₂ O ₆ X stands for Ca, Na, Fe ⁺² , Mg Y stands for Cr, Al, Mg, Mn, Fe ⁺³
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Sample S19c

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Hornblende	Ca ₂ (Mg, Fe, Al) ₅ (Al, Si) ₈ O ₂₂ (OH) ₂
Garnet (Ferrous garnet expected mostly)	X ²⁺ ₃ Y ³⁺ ₂ Si ₃ O ₁₂ X stands for Ca, Fe ²⁺ , Mn, and Mg Y stands for Al, Cr, and Fe ³⁺
Chalcopyrite	CuFeS ₂

Sample S26c

Minerals and chemical composition	
Quartz	SiO ₂
K-Feldspar	KAlSi ₃ O ₈
Plagioclase	(Na,Ca)Al ₁₋₂ Si ₃₋₂ O ₈
Calcite	CaCO ₃
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(F, OH) ₂
Biotite	K (Fe, Mg) ₃ AlSi ₃ O ₁₀ (F, OH) ₂
Clay minerals - Illite (K,H ₃ O)(Al,Mg,Fe) ₂ (Si,Al) ₄ O ₁₀ [(OH) ₂ , (H ₂ O)] - Kaolinite Al ₂ Si ₂ O ₅ (OH) ₄ - Smectite (Na,Ca) _{0.33} (Al,Mg) ₂ (Si ₄ O ₁₀)(OH) ₂ ·nH ₂ O	General formula: AlSi ₃ O ₄
Chalcopyrite	CuFeS ₂
Arsenic bearing minerals - Realgar (AsS) - Orpiment (As ₂ S ₃) - Arsenopyrite (FeAsS)	Minerals containing As in various forms.

Appendix I – Workflow of the project

Project ECTS: 10 (approximately 50 working days)

1 ECTS is equivalent to 40 working hours per week – for each working day an average of 8 hours of work was completed

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
<p>Week 1 (30-08-10 to 05-09-10)</p>	-	-	Arrival in India	Meeting with professors, welcome day	Obtain new literature - organize discussions with professionals and researchers	Visit Maner 1 st borehole location - literature study	Literature study
<p>Week 2 (06-09-10 to 12-09-10)</p>	Patna borehole (1 st day of drilling)	Patna borehole (2 nd day of visit)	Patna borehole (3 rd day of visit) - deciding borehole design parameters	Decision making day regarding further research in Maner - Meeting with researchers from CGWB	Data gathering - meeting with Dr. Sinha from Geology Department of Patna University	Literature study	Day off
<p>Week 3 (13-09-10 to 19-09-10)</p>	Data gathering - visit to CGWB and discussion with Director, Dr. Chandra	Finalizing fieldwork plan and drilling protocol	Literature study - Data and equipment gathering - visit to Geology Department (Patna College) - discussion with Dr. Sinha	Visit 1 st borehole site - setting of drilling equipment - discussion with local people and drilling planning	Local holiday - presentation in A. N. College to 1 st year students - discussion with Seema Sharma about SEM and XRD tests - purchasing sampling equipment	Drilling (Maner Borehole #1)	Drilling (Maner Borehole #1)

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Week 4 (20-09-10 to 26-09-10)	Drilling (Maner Borehole #1)	Drilling (Maner Borehole #1)	Drilling (Maner Borehole #1)	Drilling (Maner Borehole #1)	Finalizing borehole #1 - handpump installation - choosing location for borehole #2	Site preparation for drilling (Rampur) - Sample preparation for laboratory testing	Drilling (Rampur Borehole #2)
Week 5 (27-09-10 to 03-10-10)	Drilling (Rampur Borehole #2)	Drilling (Rampur Borehole #2)	Drilling (Rampur Borehole #2) - drilling overnight	Curfew due to instability between Hindus and Muslims - Borehole logging design	Sample preparation for laboratory analysis from Borehole #2 - progress meeting with Dr. Ghosh and Dr. Bose - borehole logging design	Day off - meeting with Dr. Sinha	Sample preparation from Borehole #2
Week 6 (04-09-10 to 10-10-10)	Chosing location for borehole #3 - prepping boring setting and equipment	Drilling (Hathitola Borehole #3)	Workshop CGWB - Drilling (Hathitola Borehole #3)	Drilling (Hathitola Borehole #3)	Drilling (Hathitola Borehole #3) - visit to CGWB - discussion with Dr. Sahu	Sample preparation from borehole #3	Sample preparation from borehole #3 - borehole logging design
Week 7 (11-10-10 to 17-10-10)	Day off (visit to Kolkata) ⁽¹⁾	Day off ⁽¹⁾	Day off ⁽¹⁾	Day off ⁽¹⁾	Day off ⁽¹⁾	Day off ⁽¹⁾	Day off ⁽¹⁾
Week 8 (18-10-10 to 24-10-10)	Day off (return from Kolkata) ⁽¹⁾	Writing report	Sample preparation and writing report	Writing report	Laboratory equipment set up and sample preparation	As and Fe testing in A.N.College	As and Fe testing in A.N.College - sample preparation for TOC testing

Week 9 (25-10-10 to 31-11-10)	As and Fe testing in A.N.College	Finalizing the sample tests - sample registration	Results implementation - writing report (2)				
Week 10 (01-11-10 to 07-11-10)	Results implementation - writing report (2)	Results implementation - writing report (2)	Results implementation - writing report (2)	Results implementation - writing report (2)	Results implementation - writing report (2)	Results implementation - writing report (2)	Results implementation - writing report (2)
Week 11 (08-11-10 to 14-11-10)	Results implementation - writing report (2)	Results implementation - writing report (2)	Results implementation - writing report (2)	Results implementation - writing report (2)	Results implementation - writing report (2)	Results implementation - writing report (2)	Results implementation - writing report (2)
Week 12 (15-11-10 to 21-11-10)	Results implementation - writing report (2)	Packing and preparation for travelling and return to The Netherlands	-	-	-	-	-

Regional holiday of Durga Puja. Visit to Kolkata festival during these days.

According to police instructions for foreign travellers, the area of Bihar is relatively insecure, due to the upcoming elections.

Besides this, the A.N.College campus, where major part of the work is being carried out, is shut down and utilized as a counting center for the elections. For these reasons, this part of the work is continued in Kolkata.

Appendix J – Borehole diaries

The following paragraphs summarize the drilling procedure, difficulties encountered, observations that were made while drilling and a description of the different drilling locations and situation.

Maner Fieldwork

Borehole #1 (Haldi Chhapra location)

16-09-10

Visit to Maner and preparation of drilling site for the 1st borehole. Maner is a rural area, corn is cultivated around in most of it. Abandoned channels of Ganga river can be seen around the drilling location. Wetland have been formed there. Maner block consists of a cluster of villages very densely located. Each has a primary school and Maner, the largest village, has a high school as well. For further education, children need to go to Patna, the state capital. The people in general are warm and they welcome us. Children are very curious about my presence there. We are drilling the first borehole within the property of Ram Kishan Singh, a former militarian who lives there with his children and grandchildren. None of them speaks English, but communication is easily achieved via other people. I am accompanied by Ajay Bhatt and three BSc students from A.N. College, Department of Water Management and Environment, who will contribute to the drilling procedure, while carrying their own research there as well. Their participation in this project will be included in their final Thesis. The house has an external toilet with a septic tank, which has never been used. It was installed by UNICEF, with financial contribution of both the community and the local government. It proves how social aspects are important and need to be taken into consideration when western policies are applied in developing countries, otherwise a project may fail.

The drilling equipment was set. Blessing of the equipment, according to Hindu beliefs was carried out (This is a procedure that took place before starting drilling for each one of the three boreholes). The borehole will be located next to a small stable (one cow capacity) and next to the house. The equipment comprises of the standard bamboo setting. All pipes were carried to the site.

Later we attempted to take GPS and depth measurements in the wells of Maner block (mostly the nearby villages) where As contamination was detected. Heavy rain prevented us from doing so. This task was postponed for a later stage of our fieldwork.

18-09-10

1st day of drilling. Depth reached: 54 feet.

The Ganga has risen about one meter, due to heavy rainfall during the previous days.

The drilling procedure went on as planned. Almost continuous cores were obtained. Logging and systematic sampling took place. We are very satisfied by our results. All the different layers were properly recognized and registered. Nice sunny weather, no interruptions during drilling. Everyone is very enthusiastic and we are all working accordingly.

19-09-10

2nd day of drilling. Depth reached: 70 ft

End of clayey formations that give us continuous core. This transition was encountered at 53 ft approximately. Sandy and deeper gravelly layers are drilled. Procedure is stuck at 54 ft depth due to difficulty in drilling in sandy layers. At the end of the day, the workers had to pull out all the pipes, since it would be risky to try an pull them manually the day after. Their experience from such drilling indicates that pipes get entrenched by collapsing sand and gravel layers and then, in such a depth, it is too difficult to pull them manually out. Continuing was impossible.

20-09-10**3rd day of drilling. Depth reached: 79 ft.**

Bentonite and an adapter for smaller diameter pipe needed to be purchased. As a result, we started drilling late. Previous stabilization of the borehole with Bentonite did not succeed. Sandy layers had collapsed. Re-stabilization process started. The whole day was spent on re-opening and stabilizing the borehole. No progress was made.

21-09-10**4th day of drilling. Depth reached: 88 ft.**

Drilling procedure slowly started again. We are now drilling by using the 2" diameter pipes. Mostly mineralogical study is carried out. Sandy-gravelly formations, quite homogeneous. At 81 ft, we meet groundwater, its temperature is low. Procedure is very slow, since the workers are still trying to stabilize the borehole.

22-09-10**5th day of drilling. No progress was made.**

Borehole failed to be re-drilled during the whole day. We did not manage to proceed at all. First thoughts of abandoning this borehole appeared. Giving it another try the day after would show whether it is worth continuing or not.

23-09-10**6th day of drilling. Depth reached: 160 ft - END.**

The weather is rainy.

The workers spent the whole morning trying to re-open the borehole. We took advantage of our time there to visit neighboring villages and investigate for locations for borehole #2. A High School in Rampur Diara was decided to be the best location for this.

In the afternoon, the workers managed to re-open the borehole. It was decided that we would complete the borehole in one day, since it would be impossible to re-open it the day after. Continuous sampling took place until we reached 130 ft. All samples were slurry, sand samples. After this, rain started to fall and it was already very dark. We needed to return to Patna as soon as possible for safety reasons. In addition, no sample recognition and logging would be possible, since light provided was very poor.

The drillers continued drilling until they reached 160 ft depth. Samples at some intervals were kept for me to inspect them the day after. The bore well pipes were also installed during the night.

24-09-10**Finalizing borehole #1.**

We spent the morning purchasing necessary equipment to install the hand pump.

We reached the site, drilling was completed and the pipes were installed. The samples obtained the night before were logged.

We then left for Rampur Diara to fix the location for borehole #2. It is decided to be located within the High school campus. It was initially proposed to us to drill near toilet facilities, which we were assured that they have never been used before. All the discussions were carried out with a teacher from the High school. I refused drilling there and decided to investigate all safety standards regarding drinking water before choosing the borehole location.

In general, we needed to take a small break, so we finished work by 17.30. A slight fever would not help to continue.

25-09-10

Due to feeling unhealthy and feverish, I decided to stay back in Patna with one of the students to prepare the samples from borehole #1 for testing. The rest of the students with Ajay Bhatt visited Rampur Diara to fix the borehole location, according to international drinking water safety standards for well location. This was carried out as expected. They also expanded our database of bore wells' coordinates and depths from the area.

Regarding lab work, the samples were dried the day before and manually grind today. A portion of about 5

grams for each sample is adequate for all laboratory tests. Five samples were delivered to Seema Sharma from Physics Department to be send for XRD and SEM testing, while adequate sample was stored for Arsenic and TOC testing in the laboratory. Water samples were also stored there. All field work equipment was prepared for the day after.

26-09-10

Rampur Diara Borehole #2

1st day of drilling. Reached 59 ft depth.

An agreement was signed between me and the Jagtarini High school headmaster. This agreement aimed to ensure that the toilet facilities at 60 ft distance from the bore well would be permanently shut down (there are adequate facilities in the campus) and the leaching pit at 55 ft distance from the borehole would be destroyed. Through the agreement I was officially reassured that the pit and toilets were never used. The borehole is also located at safe distance (69 ft) from a septic tank, serving the toilet facilities of another building in the campus.

The drilling procedure started. Everything proceeded according to plan and. We all carried the experience of previous drilling and sampling and work was carried out much more tidy and in more detail. Very satisfactory result.

27-09-10

2nd day of drilling. Reached 85 ft depth.

Re-opening the borehole took almost 3.5 hours. The loose sandy layers had collapsed around the tube and entrenched it, which made pulling them out and proceeding very difficult. Despite this, drilling with 5 inch diameter tubes was completed. Sandy aquifers encountered.

28-09-10

3rd day of drilling. Reached 100 ft depth.

Pipes were pulled out the day before to avoid their entrenchment in the borehole. Power was cut off from early morning to 13 pm. No work could be carried out, since water supply is provided by a pumping system that works with electricity.

Some villages were visited to obtain well GPS and depth data.

Drilling continued until the evening. Some difficulties were encountered in sandy layers, but they were overcome quite quickly.

29-09-10

4th day of drilling. Borehole completed (160 ft depth) - attended personally until 125 ft. depth.

Electricity was cut off for second day in a row. No work could be carried out during the morning. In addition the pipe that was providing the borehole with water was taken by its owner without previous warning.

Again we took advantage of this time to visit villages and fix GPS locations and depth for drinking water wells.

Drilling started approximately at 11.30 am. After many disturbances due to electricity failure, we managed to proceed in a more stable pace in the afternoon. We reached 125 ft depth by sunset. Due to instability in the area because of the upcoming elections and for safety reasons in general, I had to return to Patna at that time. Two A.N. College students, properly instructed, stayed there and collected samples every 1-2 ft. I would then obtain them in A. N. College, log them properly and prepare samples for laboratory testing.

30-09-10

Borehole # 2 completed.

Samples were logged in A.N. College.

Visit to Central Groundwater Board. They still haven't given us the requested data from their investigation

borehole in Haldi Chhapra. They are crucial for the research, but obtaining them appears to be a very difficult task.

Borehole #3 - Hathitola Primary School

04-10-10

Choosing location for Borehole #3.

Hathitola Primary School agreed to cooperate to the research. The school was funded by UNICEF. It is a public school for children that come from poor rural families and can not afford private education. It consists of two rooms for all the children. A government program is introduced, which provides free lunch for all students. It is a method of making school more attractive to them and to help their families at the same time. A kitchen is also being constructed at the site.

Due to lack of adequate water supply, we will first drill one 30 ft deep borehole and install a hand pump there to serve our boring purpose. This hand pump will then be shut down and only the deep one will be used.

We spent some time registering data from bore wells in the surrounding villages.

05-10-10

1st day of drilling.

The secondary hand pump is installed at a depth of 30 ft. The core obtained by this drilling was not logged, but was rather examined just to provide with a first insight of the formations that would be encountered while drilling the main borehole. A meeting with Dr. Dhayal and Dr. Sinha took place at the site. Local geology and lithofacies were discussed with them and useful information were provided.

06-10-10

Attending the Workshop by CGWB. Many valuable presentations were given regarding groundwater utilization, drinking water usage, waterborne diseases, social aspects and techniques applied in the area. In the afternoon, the samples for TOC testing from boreholes #1 and #2 were prepared in the laboratory of A. N. College.

07-10-10

2nd day of drilling. Depth reached: 116 ft.

Due to time pressure, it was decided that the borehole will be completed within 24 hours of continuous drilling. The procedure took place as planned. All samples were properly registered until 18.00 pm. Then heavy rain started. I had to leave the site for safety reasons, since it was already dark, but the A. N. College students stayed there to obtain samples that I would later log in the laboratory.

Drilling continued until 2.00 am., when an asymmetrical sinkhole was formed around the top of the borehole, resulting in a collapse of the hole and a sudden pause of drilling. At that point a gravel layer was reached. The large input of rainwater had probably increased the friction, causing the layer to collapse. Drilling was paused.

08-10-10

3rd day of drilling. Depth reached: 160 ft.

Drilling started early in the morning and finished

Visit to CGWB and discussion with Dr. Sahu. His research on tectonics and geomorphology of the study area resulted in a very useful and enlightening discussion regarding the structure of the area.

09-10-10

Registering the samples obtained by Borehole #3 in A.N. College laboratory. Selection of samples to be tested and appropriate preparation.

10-10-10

Preparation of samples to be tested for As, Fe, SEM and XRD. Samples to be tested for TOC were taken at my residence to be prepared there, since the upcoming elections would probably not allow us to enter the College. The Department and other laboratories will be used as counting centers.

22-10-10 to 26-10-10

Preparation of the laboratory equipment in A.N.College for As and Fe testing on the sediment samples. For the rest of the days that followed until my departure for Kolkata, As and Fe testing took place with the help of Ajay Bhatt and the students in the laboratory of A.N.College. Samples to be carried back in TU Delft for further testing by SEM, XRD and XRF methods were chosen and prepared.

Appendix K – Pictures of fieldwork and life in India



The drilling procedure. The working conditions were extremely harsh, especially during the warm monsoon period.



Sample registering on field



Exploring the Ganga River on a fishing boat

We were always welcome to share food with the local people. The cuisine was spectacular!



During a break from laboratory work.



Day off – A visit to Patna Zoo with the students.

Rural areas of Maner block.

Temple entrance – Maner

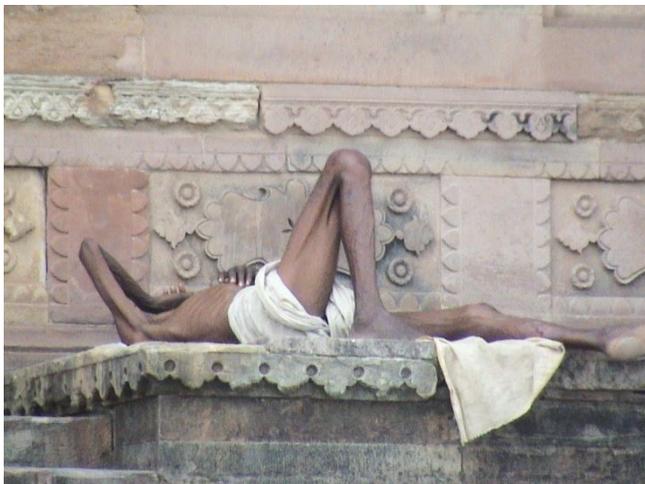
Boats sailing on the Ganga River.



Rikshaw drivers taking their midday nap.
We were under strict supervision of Bihari kids..



The impressive Durga Puja – Kolk



Appendix L – Sample pictures

Borehole #1



15-18.5 ft

18.5-25 ft

22-24 ft (Sample S7)



25-43 ft



Pebbles found at 105 ft (left)- drilling through this layer was very difficult.

Sample S5 (middle) and S9 (right) as obtained on field.



From left to right, samples S3, S2, S1, S6, S5, S4, S9, S8, S7, after they were air-dried in the laboratory.



From left to right: S12, S11, S13, S14, S15, S16, S17, S18, S19



From left to right: S20, S21, S22, S23

Borehole #2



Dark grey clay, rich in organic material (38 ft depth)



From left to right: Samples S10b, S12b, S13b, S14b



Samples S5b and S6b. Middle: Detail of Sample S5b, showing parallel lamination, rich in muscovite. Right: Detail of S6b, showing wavy lamination.



From left to right: Samples S7b, S8b, S9b, S10b. Last image on the right shows detail of S9b – wavy lamination.



From left to right: Samples S11b, S12b, S13b, S14b, S15b and S16b.



From left to right: Samples S17b, S18b, S19b, S20b, S21b, S22b and S23b (Pleistocene layer)

Borehole #3

Left: 4-11.5 ft depth.

Middle: 15.5 – 19 ft depth.

Right: 21-21.5 ft depth. Detail showing heterolithic bedding.



31-33 ft (Left: intact core, as obtained by the borehole, Middle: Cut core, showing parallel lamination in some layers). On the right image: detail of 33.6-34 ft showing wavy lamination)



From left to right: Sample S1c, S2c (heterolithic bedding), S3c (parallel lamination)



Left and middle: Detail of S4c, showing heterolithic bedding in dark gray clay, that is rich in organic material. Right: Homogenized S5c.



Air-dried samples, the sample numbers are given on the papers.



Air-dried samples. The sample numbers are given on the papers. S26c belongs to the Pleistocene layer.

