Hydro-geochemical Evolution and Arsenic Occurrence in Aquifer of Central Ganges Basin
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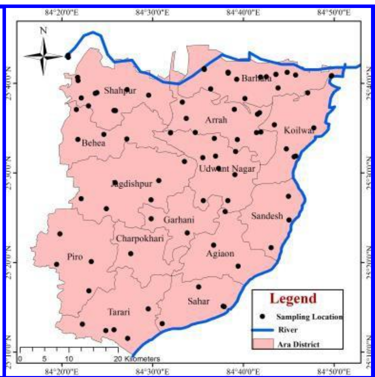

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PREFACE

Groundwater is the most important source for domestic, industrial and agricultural water supply in the world. The alluvial formation of the Ganga plain in the state of Bihar and Uttar Pradesh comprises productive soils and aquifers. The use of groundwater for irrigation and domestic purposes has increased manifolds in these states. The unplanned urbanization and industrialization have adversely affected groundwater resources in terms of both quantity and quality. Water quality challenges mainly include contamination by agricultural runoff, sewage leakage, seepage into groundwater, and geogenic contamination such as arsenic, fluoride, etc. Arsenic (As) contaminated drinking water is the most challenging environmental problem and is currently affecting millions of people across the globe. Chronic exposure to groundwater having an arsenic concentration of more than 10 μg/L leads to numerous adverse health impacts.

Many researchers have reported rampant occurrence of As with elevated concentration in groundwater in the middle and lower Ganga plain. However, studies carried out in the middle Ganga plain to understand arsenic geochemical behavior, seasonal change of arsenic, understanding groundwater recharge and its effect on arsenic mobilization in groundwater, its relation with declining/rising groundwater level, mineralogical analysis, etc. are very few. The present study broadly explores the causes of rampant occurrence of arsenic and processes controlling the mobilization of As in groundwater of the Bhojpur district, Bihar located in the central Ganga basin. I hope that the outcome of this study might have filled some of the knowledge gaps mentioned above. The output of the study may help demarcating safe aquifer, developing improved monitoring and mitigation measures at the regional level, which may help develop the methodology for arsenic mitigation at national level.

This report has been prepared by Dr. Sumant Kumar, Scientist-D as Principal Investigator along with a team of NIH's Scientists and staff (Dr. Sudhir Kumar, Sc.-G, Dr. Rajesh Singh, Sc.-D, Dr. Gopal Krishan, Sc.-D, Mrs. Anju Choudhary, SRA, Mr. Ramchander, SRA) with Minor Water Resources Department, Govt. of Bihar as the partner organization and IIT Roorkee (Prof. Brijesh K. Yadav) and NIT Patna (Prof. N.S. Maurya) as the technical collaborator.

[Sudhir Kumar]

Director, National Institute of Hydrology, Roorkee

Project Team	
Lead organization	Dr. Sumant Kumar, Sc.-D, GWHD (PI) Dr. Rajesh Singh, Sc.-D, EHD (Co-PI) Dr. Sudhir Kumar, Sc.-G & Head, HID Dr. Gopal Krishan, Sc.-D, GWHD Mrs. Anju Choudhary, SRA, GWHD Mr. Ram Chander, SRA, GWHD *Project Staffs:* Dr. Ravi Kumar Saini, RA Mr. Vinod Kumar, PA-I Mr. Mohit Kumar, PA **Lead Organization-** National Institute of Hydrology, Roorkee, Jal Vigyan Bhawan, Roorkee - 247 667. **IA-** Minor Water Resources Department, Govt. of Bihar, New Secretariat, Patna-800015.
Partner organization/s	Er. Ramshankar Ojha, AE (PI) Er. Satyendra Kumar Gupta, JE (Co-PI) **Partner Organization or IA**: Minor Water Resources Department, Govt. of Bihar, New Secretariat, Patna-800015 **Technical Collaborators** Prof. Brijesh K. Yadav, IIT Roorkee Prof. N.S. Maurya, NIT Patna
Consultant/s, if any (enter each consultant in a separate row)	NA

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Abstract

Groundwater abstraction from the alluvial aquifer system is reported to be approximately one-fourth of the world's total groundwater abstraction and supports the agricultural activity of south Asia. The alluvial formation of the Ganga plain in the state of Bihar and Uttar Pradesh comprises productive soils and aquifers. The use of groundwater for irrigation and domestic purposes has increased manifolds in these states. The Indo-Gangetic aquifer is one of the most heavily exploited aquifers in the world. The excessive withdrawal of groundwater has adversely affected groundwater resources in terms of both quantity and quality. Water quality challenges mainly include contamination by agricultural runoff, sewage leakage, sepage into groundwater, and geogenic contamination such as arsenic, fluoride, etc. Arsenic (As) contaminated drinking water is the most challenging environmental problem and is currently affecting around 220 million people across the globe; out of which, around 94% affected people are in Asia. Chronic exposure to groundwater having arsenic concentration more than 10 μg/L leads to numerous adverse health impacts like lower intelligence quotients, type 2 diabetes, skin lesions, melanosis, keratosis, cancer, etc. Arsenic contamination in water is producing the greatest impact on livelihoods in terms of public health and thus arsenic calamity in the Ganga river basin has put millions of population in danger.

Many researchers have reported rampant occurrence of As with elevated concentration in drinking water by evaluating groundwater quality in the middle and lower Ganga plain. However, studies to understand arsenic geochemical behavior, seasonal change of arsenic, understanding groundwater recharge and its effect on As mobilization in groundwater,

its relationwith declining/rising groundwater level, mineralogical analysis and leaching of arsenic from solid to groundwater phase, etc. in the middle Ganga Plain are very few. Thus, there is a considerable knowledge gap in understanding the role of anthropogenic and geogenic factors in controlling the mechanism of arsenic mobilization in the middle Ganga basin. The present study explores the causes of rampant occurrence of arsenic and processes controlling the mobilization of As in groundwater of the Bhojpur district, Bihar located in the central Ganga basin. The Bhojpur district isbounded by the rivers Ganga and Ghaghra in the north and east. The objectives framed under the study are (i) determination of the spatio-temporal variation of arsenic along with other water quality parameters in groundwater, (ii) delineation of arsenic safe zone for drinking water supply, (iii) evaluation of the controls of hydro-geology on arsenic contamination through monitoring of contaminated aquifer and sediment characterization, and (iv) identification of the mechanism of release and transport of arsenic in GW through a column experiment. The significance of the study is to help demarcate safe aquifers, and develop improved monitoring and mitigation measures at the regional level. To achieve the above objectives, 94 water samples to analyze the water chemistry, and 62 samples for isotopic analysis, were collected during the Nov. 2018 (post- monsoon season) from the entire district by making a grid of size 4 km x 4 km in on northern side (along river Ganga) and 8 km x 8 km in the southern part of the study area. The groundwater samples collected were generally from hand pumps with depths ranging from 15 to 80 m. After understanding the spatial variation of water quality parameters, particularly arsenic, detailed investigation started in arsenic-affected areas. The water samples (45 Nos.) from pre & post monsoon season (year 2019) were collected from the arsenic affected area. A total of eight shallow piezometers (24.4-42.6 m depth) was constructed in the study area for sediment characterization and water quality monitoring. The composite sediments samples were collected depth-wise from top to bottom at an interval of 3 m until changes in the lithology were observed while drilling. The XRD and XRF analysis were carried out for mineralogical study. The sediments were also used for performing batch and column experiments.

Based on the analysis, the geochemistry of the groundwater is found mainly controlled by carbonate weathering with less contribution from silicate weathering in the study area. It is observed that the dissolution/weathering of carbonate rock acts as the major contributor for Ca, Mg, and HCO_3; alumino-silicates minerals are the major contributor for Na, K, and SiO_2. Similar observations were also made by other researchers regarding the geochemistry in the middle Ganga plain. The hydro- geochemical facies for groundwater in the study area is Ca-Mg-HCO_3 type. In the study area (covering the entire Bhojpur district), the concentration of arsenic in groundwater during the post-monsoon season (year 2018) varied between not detected (ND) to 206 ppb (Semaria ojha Patti of Sahpur block) with the average concentration of 15 ppb. The results revealed that about 30 % of analyzed groundwater samples had As concentration above the acceptable limit (10 ppb) and 8 % exceeded the permissible limit (50 ppb) as prescribed by BIS (2012) for drinking purposes. Spatial distribution map of arsenic showed that the northern part of the study area associated with the Ganga alluvium plain was more arsenic affected in comparison with the southern part of the district. The As concentration was found almost negligible in river water, i.e. the Ganga water and the Sone water samples, that varied between 2 to 5 ppb and ND to 2 ppb respectively. On the other hand, in the pre-monsoon samples (year 2019) results from arsenic affected areas suggested that about ~60% of water samples were enriched with dissolved As concentrations >10 µg/L, and it ranged from ND to 337 ppb (average 78 ppb). Arsenic in groundwater exhibited a wide spatial variation, even more than 100 times within a distance of 200 m.

The elevated concentration samples area was mainly from Sahapur and Barahara block of the study area, which is located in the younger alluvium of the Ganga flood plain. Based on depth-wise sampling, arsenic contamination was mainly found in the-depth range 20 m to 60 m and As conc. decreased rapidly below 60 m. It indicated that only the upper aquifer is contaminated by As. The temporal variation of arsenic indicated that it is more pronounced in the pre-monsoon season as compared to the post-monsoon season and approximately 10-40 % reduction in As concentration was observed in the post-monsoon season. For the present case, variations in the arsenic concentrations in groundwater are supposed to be due to the dilution effect and changes in the redox conditions, which is expected to cause desorption of arsenic from metal oxides. The parameters such as oxidation-reduction potential (ORP), Fe, Mn, NO_3 and SO_4 are the main redox parameters, which control the release of As in groundwater. A good correlation between As and ORP (0.61) suggested a redox-dependent mobilization played an important role in As liberation. Fe was found positively correlated with

As, (0.627), but As showed a weak positive correlation with Mn, which indicated that As might get mobilized from dissolution/desorption from the iron hydroxides in the sediment. It is evidently noticed that arsenic was high when ORP was negative and DO was less, reflecting the occurrence of arsenic in reducing conditions.

The isotopic analysis was also carried out to identify the zones of recharge and recharge sources in the study area. The Sone River is highly enriched in isotopic signatures as compared to the Ganga River, indicating a highly enriched source or evaporation of the water during the travel from the Vindhyan Mountains. The spatial variation of $\delta^{18}O$ revealed that there was a distinct isotopic difference between groundwater samples from the proximity of the Ganga and the Sone River. The Ganga River has an average $\delta^{18}O$ value of -5.78‰ whereas the isotopic value for the Sone River remained -3.17%. The groundwater samples for both the river water region ranged close to its river accompanying it, indicating depleted groundwater near to the Ganga River and enriched groundwater close to the Sone River. The enriched value of groundwater samples close to the Sone River has been due to the recharge through the Sone River, while the groundwater close to the Ganga was contributed from the Ganga River. This also corroborated from the groundwater flow direction, which was found toward the Ganga River. The isotopic signature of the groundwater also indicated the vertical mixing of groundwater from the irrigation return flow or other sources.

The mineralogical properties of sediment were studied using X-Ray Diffraction (XRD) and X-ray fluorescence (XRF) technique for the selected samples. From XRD analysis, it was found that quartz, clay and feldspar were the major minerals for most of the samples, whereas goethite and dolomite were present rarely in few samples only as the minor minerals. However, some minor peaks were observed which indicated the arsenic-bearing minerals present in the soil sample such as, the presence of iron arsenate ($Fe_2As_4O_{12}$). In general, the analysis revealed that all samples contained major amounts of SiO_2 as well as substantial Al_2O_3 concentrations. More specifically, average major elements of all the sediment samples indicated a predominant SiO_2 mass component (37.4% - 50.0%) with significant Al_2O_3 (4.0% - 16.2%), Fe_2O_3 (1.7% -10.0%), MnO (0.1% - 6.37%) and CaO (0.8 - 5.2 %) contributions; a few percent of K_2O (1.7% -3.3%), MgO (0.2 - 1.8 %), P_2O_5 (0.1% - 0.9%) and TiO_2 (0.3% - 1.0%), as well astrace amounts (<1%) of SO_3, Cr_2O_3, NaO, ZnO, CuO, BaO, SrO and NiO. The arsenic concentration

in the sediment samples varied from 1 mg/Kg 19 mg/Kg. Sediment samples were also analyzed for organic matter concentrations. The results indicated that organic matter was found less whereas As and Fe were found more concentrated in the depth range of 9-10.6 m, which also supported the mobilization of arsenic in groundwater by microbial reductive dissolution of iron oxides from the aquifer consisting of organic-rich clay.

The batch and column experiment were performed to study the leaching of arsenic from sediment to water phase. Initially, the batch experiment was performed on contaminated soil (Semaria village sediment) for a single run of an experiment for 8 days. It was observed that the maximum arsenic leaching (52 µg/Kg) found on 1st day followed by 2nd (34.6 µg/Kg) and 3rd day (38 µg/Kg). After that, leaching rate was found to be constant i.e. 12 µg/Kg. The water mixed with sediment for batch experiment was artificially made groundwater (concentration of salts and pH (7.35) was kept same as it was in the groundwater of Semaria village). In the second run of the experiment, the pH was varied from 6 to 8.5 and it was noticed that maximum arsenic leaches at pH 8. After completion of the batch experiment, column experiment was started with a packing of contaminated soil in a column with flow rate of 2 ml/min of artificially made groundwater. The constant leaching rate of arsenic from sediment was found to be 4 ppb/day.

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1.0. INTRODUCTION

Groundwater is the most important source of domestic, industrial and agricultural water supply in the world. It is estimated that approximately one third of the world's population uses groundwater for drinking purpose (Nickson et al. 2005). Arsenic contaminated drinking water is the most challenging environmental problem and is currently affecting around 94 million to 220 million people across the globe, out of which around 94% affected people are in Asia (Podgorski and Berg, 2020). Chronic exposure to groundwaterhaving an arsenic concentration of more than 10 µg/L leads to numerous adverse health impacts like lower intelligence quotients, type 2 diabetes, skin lesions, melanosis, keratosis, and cancer (Ravenscroft et al., 2011; Wasserman et al., 2014, Kumar et al., 2021). Elevated concentrations of As has been observed in groundwater of the United States, Canada, Brazil, Argentina, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Pakistan, Bangladesh, Cambodia, China, Georgia, India, Indonesia, Iran, Japan, Jordan, Laos, Kazakhstan, Korea, Malaysia, Mongolia, Myanmar, Nepal, Bolivia, Ireland, Mexico, Argentina, Botswana, Ethiopia, Ghana, Morocco, Nigeria, South Africa, Tanzania, Togo, Zimbabwe, France, Germany, Greece, Hungary, Romania, Croatia, Serbia, Turkey, Spain, Ireland, United Kingdom and Australia etc. (Bundschuh et al., 2020; Quino-Lima et al., 2020; Mukherjee et al., 2021; Shaji et al., 2021). Most of the areas with high As concentration in the groundwater are in the river floodplains or their proximity. Groundwater abstraction from the alluvial aquifer system is reported to be approximately one-fourth of the world's total groundwater abstraction (Wada et al., 2010) and supports the agricultural activity of south Asia (Shah, 2009). The Indo- Gangetic aquifer is one of the heavily exploited aquifer in the world (Bonsor et al., 2017, MacDonald et al., 2016). The alluvial formation in the Ganga plain in the state of Bihar and Uttar Pradesh comprises productive soils and aquifers. The use for irrigation and domestic purposes has increased manifold in these states. The excessive withdrawal of groundwater has adversely affected groundwater resources both in terms of quantity and quality (Gurjar et al., 2019). Water quality challenges mainly includes contamination by agricultural runoff, sewage leakage and seepage into groundwater and geogenic contamination such as arsenic, fluoride etc. Arsenic (As) contamination of water isproducing the greatest impact on livelihoods in terms of public health and thus arsenic calamity in the Ganga river basin put millions of population in danger (Chakraborti et al., 2018).

Arsenic is found in the natural environment in the Earth's crust, water and air. The most common oxidation states for arsenic are: -3 (arsenides: usually alloy-like intermetallic compounds), +3 (arsenites (As (III)), and most organo-arsenic compounds), and +5 (arsenates (As(V)): the most stable inorganic arsenic oxy-compounds. It can exist in organic and inorganic form. Inorganic arsenic is generally more toxic than organic arsenic. Inorganic arsenic occurs naturally in many types of rocks and it is generally found with sulphide ore arsenopyrite. Inorganic arsenic compounds known to be human carcinogens. Arsenic in elemental form is insoluble in water but it is soluble in oxidised form. Arsenic is a natural constituent in bedrock and soil. It usually occurs at low concentrations (average 1–2 mg/kg) in the Earth's crust (Bhattacharya et al., 2002), but may be concentrated in certain rock types and especially in gold and sulphide-bearing oredeposits and occurrences. Pyrite [FeS2; or arsenian pyrite Fe(AsS)2] and arsenopyrite [FeAsS] are typical sulphide minerals containing As. These minerals are relatively stable in the bedrock and in deep soil under reducing and near-neutral conditions. However, the mobility of As is largely dependent on changes in the pH and redox conditions resulting from natural processes (e.g. microbial activity) or anthropogenic disturbance of earth materials (e.g. mining) (Smedley and Kinniburgh, 2002). The behavior of As is also dependent on its oxidation state, As(III) and As(V) being the most commonly occurring inorganic species in the groundwater environment (Smedley and Kinniburgh, 2002). As commonly precipitates as Fe(III) arsenates or adsorbs onto Fe(III)oxides and Fe(III) oxy- hydroxides. However, these minerals are usually metastable and depending on the pH andredox conditions, can be subject to dissolution (Smedley and Kinniburgh, 2002). It is also necessary to understand the consequences of human actions (such as agriculture, drainage, the use of aquifers as a source of potable water or irrigation, or excavating in areas with naturally high concentrations of As that may help to prevent human exposure to this toxic and carcinogenic element.

Weathering processes of rocks and minerals appears to be a major source of arsenic found in soils. Because it accumulates due to weathering and translocation in colloid fractions, the arsenic concentration is usually higher in soils than in parent rocks. Under typical soil forming conditions, the nature of arsenic in soil is controlled by the lithology of parent rock materials, volcanic activity, bioactivity, weathering history, transport, sorption, and precipitation.

The river Ganga and its major tributaries originate from the Himalaya and carry lots of sediment and these sediments determine the chemistry of water. In the mid Holocene period, the river Ganga likely to have transported metals from Himalaya to the plains by erosion and sedimentation (Chakraborti et al., 2004). The rivers originating from the Siwalik Hills are reported to release more arsenic and heavy metals from their sediments in comparison to those major rivers originating from the Higher Himalaya (Kansakar, 2004). The geology of Himalaya region may be classified into three region (i) Higher Himalayan unit comprising of granites, gneisses, schist, marbles with carbonates and calc-silicates (Kansakar, 2004). (ii) The Lesser Himalaya consisting of shales, slates, limestones and dolomites. The exposed crystalline rocks in Lesser Himalaya are granites, schists, gneisses, calc-silicates and amphibolites (Kansakar, 2004). (iii) The Siwaliks mainly consisting of the eroded materials transported by the Himalayan rivers from the Higher Himalayan and Lesser Himalaya (Quade et al., 1997). The Ganga plain region starts from Haridwar, Uttarakhand and the Ganga enters the plain area after crossing the Siwaliks ranges. The chemistry of the river water depends on numerous sources and processes such as chemical weathering of rocks and atmospheric deposition etc. The characteristic of chemical weathering depends upon many factors viz. parent rock type, topography, climate and biological activity. The weathering plays a major role in the geochemistry of groundwater as the chemical weathering help in the mobilization and redistribution of major and trace elements in the environment by various process like dissolution of minerals, co-precipitation and ion exchange etc. The dissolution and leaching of metal under influence of monsoon rain is of serious environmental concern (Oke et al., 2012).The nature of geological formation and the residence time of groundwater influences the quality of groundwater due to rock-water interaction.

In order to study the causes of arsenic occurrence in central Ganga basin (Bhojpur district) and its mobilization from solid to water phase, it is planned to carry out mineralogical, geochemical and mobilization study by performing column experiment. However, in the present final report, the work viz. literature review, study area description, groundwater geochemistry, mineralogical and geochemical results of few sediment samples (56 sediment samples were collected during eight piezometer installation in the study area) are presented. Motivation to study in Bhojpur district and the objectives framed under the study are mentioned in subsequent paragraph.

The enriched As concentration in the aquifer of sedimentary basin is largely distributed across the world, including the Himalayan basins: Indus, Ganges, Brahmaputra, etc. (Kumar et al., 2017, Ravindra and Mor, 2019, Kumar and Singh, 2020). There are several hypotheses proposed to comprehend the geogenic sources of As in groundwater primarily based on plate-tectonic theories including structural deformation and differentiation of Earth (Mukhaerjee et al., 2019, Lone et al., 2020). Arsenic has been suggested to be introduced into groundwater through the (i) oxidation of aquifer arsenical pyrite and other arsenic bearing sulfide minerals, (ii) reductive dissolution of arsenic rich Fe(III) oxy-hydroxides and hydroxides present in aquifer, and (iii) exchange of adsorbed arsenic with other competitive anions (phosphate, bicarbonate and silicate). Nevertheless, the reductive dissolutions of arsenic rich Fe (III) oxy-hydroxides and/or hydroxides were widely accepted to be the main mechanism of direct arsenic mobilization. Although arsenic exists in alluvial sediments, its origin is believed to be related to the outbreaks of bedrocks.

The processes of formation of Himalayas have been linked with arsenic occurrence in aquifers of Himalayan basins/sub-basins (Mukhaerjee et al., 2014). The unconsolidated alluvial (recent age) including fluvial and lake deposits of these basins liberates arsenic as a consequence of complex hydro-geochemical and bio-geochemical processes (Jeelani et al., 2020). The hydro-geochemical processes depend on various factors such as sedimentlogical settings, sedimentation deposits history, adsorption and desorption behaviour of sediments etc. (Bhowmick et al., 2013). The bio-geochemical interaction is regulated by several factors such as dissolved organic matter, types of microbes present in the sediment etc. It also depends on anthropogenic activities such as mixing of domestic sewage, recharge from contaminated ponds etc. (McArthur et al., 2001). The modification in hydrological environment and alteration in groundwater flow path plays akey role in guiding arsenic mobilization in aquifers. For the above purpose, the study of isotopic composition of precipitation, surface water and groundwater helps in understanding the recharge mechanism of groundwater and its effect on groundwater As mobilization into aquifers (Ali et al., 2019). The stable isotopes of Hydrogen ($\delta\ ^{2}H$) and Oxygen ($\delta\ ^{18}O$) are commonly used as an environmental tracer to understand the hydrological processes of surface water and groundwater interactions and recharge mechanism (Mushtaq et al., 2018).

Many researchers have reported rampant occurrence of As with elevated concentration in drinking water by evaluating groundwater quality in the middle and lower Ganga plain (Kumar et al., 2010, Shah, 2015, Saha and Sahu, 2016). However, very few studies have been carried out in the middle Ganga plain to understand arsenic geochemical behavior, seasonal change of arsenic, understanding groundwater recharge and its effect on arsenic mobilization in groundwater, its relation with declining/rising groundwater level, mineralogical analysis and leaching of arsenic from solid to groundwater phase etc. Thus, there is a considerable knowledge gap in understanding the role of anthropogenic and geogenic factors in controlling the mechanism of arsenic mobilization in the middle Ganga basin. The present study explores the causes of rampant occurrence of arsenic and processes controlling the mobilization of As in groundwater of the Bhojpur district, Bihar located in central Ganga basin. The Bhojpur district is bounded by the rivers Ganges and Ghaghra in the north and east. The objectives framed under the study are: (i) determination of the spatio-temporal variation of arsenic along with other water quality parameters in groundwater, (ii) delineation of arsenic safe zone for drinking water supply, (iii) evaluation of the controls of hydro-geology on arsenic contamination through monitoring of contaminated aquifer and sediment characterization, and (iv) identification of the mechanism of release and transport of arsenic in GW through a column experiment. The significance of the study is to help in demarcating safe aquifer, improved monitoring and mitigation measures at regional level.

2.0. LITERATURE REVIEW

Ground water is an essential component of water resources which is being utilized for drinking, irrigation and industrial purposes. There is growing concern on deterioration of ground water quality due to geo-genic and anthropogenic activities. The quality of ground water has undergone a change to an extent that the use of such water could be hazardous. Increase in overall salinity of the ground water and/or presence of high concentrations of fluoride, nitrate, iron, arsenic, total hardness and few toxic metal ions have been noticed in large areas in several states of India. Ground water contains wide varieties of dissolved inorganic chemical constituents in various concentrations as a result of chemical and biochemical interactions between water and the geological materials through which it flows and to a lesser extent because of contribution from the atmosphereand surface water bodies. Contamination of groundwater through naturally occurring arsenic (As) has been reported in many countries around the world, particularly in Southeast Asia causing serious threat to humans (Ahmed et al., 2009; Bhattacharya et al., 2014; Jimmy et al., 2013; Huyen et al., 2019, Kumar et al., 2021a). This has received significant attention in the last three decades due to its serious health effects on millions of people and has been termed “the biggest As calamity in the world” (Smith et al., 2000,). High-As groundwater areas have been found in Argentina, Chile, Mexico, Hungary, India, Bangladesh and Vietnam etc.

In India, high concentration of arsenic beyond permissible limit of 0.05 mg/l in ground water has been reported from 86 districts of 10 States (CGWB Website: http://cgwb.gov.in/wqoverview.html). Investigation over the years reported that elevated As (more than 10 µg/L drinking-water standard set by World Health Organization) has been widely present in the potable groundwater chiefly in three states of Gangetic plains, and as many as 15 million residents in West Bengal, 10 million in Bihar and 20 million in Uttar Pradesh (UP) have been at risk. The scale of the problem in terms of population exposed to high As concentrations is greatest in the Bengal basin This led to many hydrogeological studies in the Gangetic plain to identify the source and cause of elevated groundwater As-contamination (Kumar et al., 2019).

Arsenic is a toxic element, known as class (I) human carcinogen and widely distributed in the environment as both inorganic and organic forms (Ravenscroft et al., 2014). In general, the inorganic forms (arsenite and arsenate) of As are much more toxic than the organic forms (mono methyl arsonic acid, dimethyl arsinic acid, arsenobetaine etc.) of As. Arsenite is generally more toxic than arsenate and humans are exposed to both forms of inorganic As from water and food. The toxicity of arsenic (As) has long been evident, but only during the 1990s did awareness of human exposure to As through drinking water raise concern, when the problem was discovered in West Bengal in India and in Bangladesh (Smith et al., 2000). High concentrations of arsenic in groundwater and sediments occur in many parts of the world due to industrial contamination and agro- chemical applications as well as natural processes (Rahman et al., 2014).

A considerable amount of research has been carried out to better understand As contamination in drinking water and food supplies. It was understood that chronic exposure to As may cause health problems. Recent studies have focused on As in hydrological processes between the geosphere, hydrosphere, and biosphere (e.g., Bhattacharya et al., 2014; Bundschuhet al., 2013, Kumar et al., 2021a,b). During 1992,the researchers from School of Environmental Studies (SOES) noticed something unusual while working in arsenic affected Gobindapur village, Swarupnagar block, North24-Parganas district, West Bengal. In due course of time, SOES began to gather more andmore information about arsenic problem in those parts of Bangladesh adjacent to the arsenic affected areas of West Bengal. SOES analyzed the hair, nail, skin-scale and urine of the patients who came to Kolkata for treatment and in most of the biological samples, arsenic was found in elevated level. In India, the ground water arsenic contamination wasfirst reported from West Bengal (Garai et al., 1984). After that a number of other states had chronically affected with arsenic pollution (Chakraborti et al., 2008). Presently the most acute arsenic contaminated site in the world is the Ganges-Brahmaputra-Meghna plain with concentration sometime > 4 ppm (Rahman et al., 2006). Some cases ofarsenical dermatitis in few districts of West Bengal were reported during 1980. The occurrences of As in groundwater in West Bengal have been widely reported from the districts of Maldah, Murshidabad, Nadia, North & South 24 Parganas, Burdwan, Howrah and Hooghly, and more recent observations from Kolkata, North & South Dinajpur districts (SOES, 2011). The high As groundwater in West Bengal stretches ~400 km (Maldah district in the north to South 24 Parganas district in the south) and was typically characterized by heterogeneous and patchy distribution of hot spots, interspersed with low/safe As-areas. Contamination of groundwater by naturally occurring arsenic has recently become an alarming environmental problem in the deltaic plain of the Ganges– Meghna–Brahmaputra (G–M–B) rivers in Bangladesh and west

Bengal (Nickson et al., 1998; Acharyya et al., 1999). Groundwater arsenic contamination in West Bengal, India and adjoining Bangladesh is well publicized and perhaps one of the most grotesque natural calamities of the world related to drinking water. A preliminary survey during January-February 2004 in Assam showed 26% of 137 hand tube wells analyzed in 2 districts had an arsenic concentration above 50 μg/L (Chakraborti et al., 2003).

Several investigations studied on Gangetic plains during the last decade 2003-2013 and reveals that the eastern half of the Middle Ganga Plain (MGP) is mainly affected by heavy metal ion contamination, particularly As in the shallow aquifer. Arsenic contamination of tube wells in the middle Gangetic plain was first reported in 2002 in Semria Ojha Patti village (area 4 km^2), Sahapur block in the Bhojpur district of Bihar, India (Chakraborti et al., 2003). Bhojpur district situated along the right bank of the riversGanga and Sone. It is reported that the skin lesions and unusual As concentrations in nail,urine and hair of the affected persons. About 89% geographical area of Bihar (~94,000 km^2) is located in the middle Gangetic plain and is known for surplus food production and intensive groundwater extraction for drinking and irrigation (Saha, 2009). It was reported that 57 blocks in 15 districts of Bihar are As-affected. Several attempts havebeen made to investigate the concentration of As in groundwater, health effect due to As toxicity in the middle Ganga plain of Bihar (Chakraborti et al., 2003; Kumar et al., 2010).Later, more attention was paid by researchers or research organisations and agencies suchas central ground water board (CGWB), government of India, public health engineering department (PHED), Government of Bihar. Polluted hand pumps (more than 50 ppb As) were identified and marked as red, and informed to public that these hand pumps are not suitable for drinking purposes. The widespread As contaminations in shallow aquifers were identified in floodplains of the Himalayan-origin rivers (Kumar et al., 2012; Kumar et al, 2016). Saha et al. (2011) studied the aquifer geometry in Bhojpur and along with other districts such as Buxar, Patna and Samastipur. Government of India, (2011) report states that in middle Ganga plains, the first aquifer host the As groundwater, and goes up to the depth of 90 m below ground. The second and third aquifer systems, exhibits lowAs conc. (less than10 ppb), are located at the depth ranges of 100-160 m and 180-340 m below ground, respectively. Chakraborti et al. (2018) reviewed the impacts of arsenic contamination on human health in chronically exposed population in the Ganga river basin. Nickson et al. (2007) supported by UNICEF studied the 11 districts of Bihar (which includes 50 blocks) and tested As with the field testing kit. The result reveals that 26.4 % of 5420 water samples had arsenic above 50 μg/l from Bhojpur district of Bihar.In the year 2016, Chakraborti et al. (2016) investigated the biological samples (hair, nail, and urine) to determine the recent and past exposure of arsenic as well as people sub- clinically affected and also found that arsenic exposed women with severe skin lesions had adversely affected their pregnancies. They reported the distribution of arsenic in groundwater and the prevalence of arsenic toxicity including arsenical skin lesions, arsenic-induced neurotoxicity, and pregnancy outcome among local inhabitants of Shahpur block, Bhojpur district.

There are several unexplained questions about arsenic contamination and transport, including the source of As-enriched sediments in the aquifers and the mechanism by which arsenic is mobilized into groundwater. The central Gangetic basin comprising mainly Bihar and Uttar Pradesh are one of India's largest fluvial systems and most populous regions. In recent few decades, the increasing demand of groundwater for domestic, irrigation and industry coupled with the growing population led to the extensive exploitations of fresh and potable groundwater. Nowadays, there is a problemof safe and potable groundwater in this region as most of the areas are exposed to groundwater As contamination. To study the source of groundwater recharge and its influence to the arsenic occurrences, isotopic analysis has also been carried out by few investigators (Mushtaq et al., 2018; Jeelani et al., 2020; Mukherjee et al., 2021). The stable isotopes (δ18O and δ2H) are widely used to identify the groundwater recharge sources and zones (Clark and Fritz, 1997; Williams and Rodoni, 1997; Joshi et al., 2018, 2020), the interaction between surface water and groundwater (Dincer et al., 1970; Wassenaar et al., 2011) in the hydrologic systems. Numerous studies have focused on determining the isotopic composition of precipitation for identification of the source of water (Kumar et al., 2010; Singh et al., 2013a; Semwal et al., 2020), altitude effect, waterbalance studies and hydrograph separation, groundwater dynamics (Navada et al., 1993; Gupta and Deshpande, 2005; Kumar et al., 2011), and hydrodynamics (Krishnamurthy and Bhattacharya, 1991; Singh et al., 2013a; Shah and Umar, 2015). Hydrogeochemical and isotopic assessment on solute distribution, chemical evolution and recharge of groundwater and their interrelation will help understand the mechanism controlling the mobilization of As and its evolution in the central Gangetic Plain.

3.0. STUDY AREA

Bhojpur district is located in the south-western part of Bihar covering an area of 2395 sq.km, lies in between 25º10’ and 25º40’ North latitudes and 83º 45’ and 84º 45’ East longitudes with total population of 27,20,155 as per 2011 census. The district is bounded by Ganga river in north and Son river in east. The entire district forms an interfluves zone of Ganga & Son rivers and possesses plain flat topography. The district has three sub divisions namely Ara Sadar, Jagdishpur and Piro. The blocks of the district include Ara Sadar, Udwantnagar, Jagdishpur, Koilwar, Sahar, Barhara, Sandesh, Shahpur, Charpokhari, Piro, Tarari, Bihia, Agiawon and Garhani. The present study focus on entire district consisting of 14 blocks as shown in Fig. 3.1.

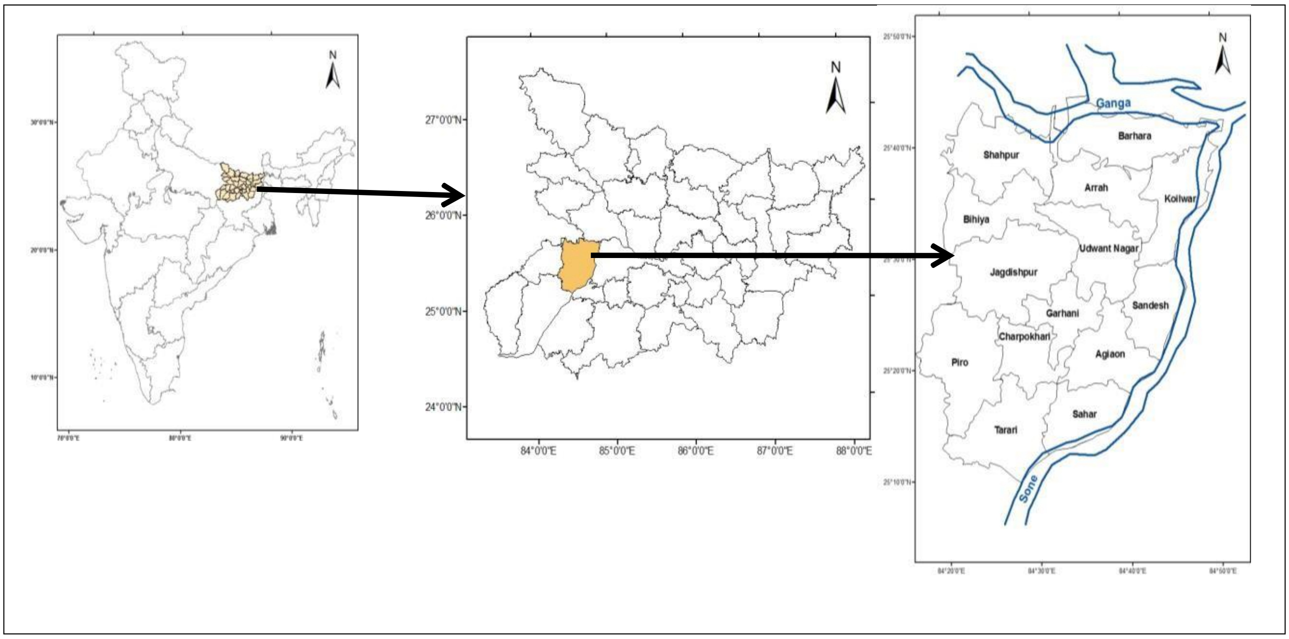


Figure 3.1: Map showing the location map of study area (Bhojpur district, Bihar)

3.1 Climate and Rainfall

Warm and humid climate prevails in the district. The temperature touches 39ºC on an average during the months of April and May, whereas minimum temperature decreases upto 6.3ºC during the month of January. In the study area, monsoon starts mostly from themid of June and continues up to the end of the September. The normal rainfall of the district is 1080 mm/yr. and the annual rainfall varies within 1025 to 1106 mm (CGWB, 2013). About 85.46 % of the total annual rainfall is obtained during monsoon period and the rest (only 14.54 % approximately) comes in the months of November to May of non- monsoon period.

After month of February, there is a steady increase in temperatures and May is generally the hottest month with the mean daily maximum temperature at 41.8ºC and the mean daily minimum at 25.4ºC. The relative humidity is generally high during thesouth-west monsoon season, being 70%.

3.2 Geological and Geomorphological Characteristics

The river Ganga originates from the Himalaya and transports sediments through its course of travelling in the plain area. The deposited sediments determine the water chemistry of the area due to several processes such as rock weathering, rock-water interaction etc. Alluvial soils are mainly formed due to sediment deposits by the Indo-Gangetic-Brahmaputra rivers and Himalayan rocks form the parent material. Geologically, the alluvial soils are divided into younger and older alluvium and they are best suited for agriculture. The older alluvium represents the upland alluvial tract whereas younger alluvium forms the flood plains. The geological formations met within the district are gangetic alluvium consisting of younger and older alluvium (Fig. 3.2). The age of these formations range from upper Pleistocene to Recent (Table 3.1). The district is covered with alluvium (major aquifer system) and hard rocks of Vindhyan Super group are situated at the south western side beyond the district boundary (CGWB, 2013). The central and southern parts are covered with Older Alluvium and older flood plains while the north and northeast parts of the district are covered with Newer Alluvium and youngerflood plains (Diara formations). The whole study area has a common slope towards the north and northeast. The common elevation with respect to mean sea level is 50-90 m and approximately the gradient is 0.6 m/km from south to north.

Figure 3.2: Geological map of the study area showing Younger and Older alluvium formation

The district in general possesses alluvium soil and the soils are of poorly drained type. The area adjoining the rivers Ganga, Son, Dharmawati, and Gangi consists of sandy loam, loamy sand and sand, whereas, the area away from the river channels consist of silty sand to sandy silt. Fig. 3.3 shows the drainage network of the study area. The soils in common are fine textured away from the river course and rivulets and coarse textured along their courses.

Table 3.1: Stratigraphic sequence of formation type in Bhojpur dist. (Ref: CGWB,2013)

Group	**Formation**	**Sediments types**	**Age**
Upper Pleistocene	Newer Alluvium	Mostly Fluvial deposits unconsolidated sand gravels, silts and clays mostly flood plain & back swamp deposits confined mainly to Son and Ganga river coarse.	Recent
Lower Pleistocene	Older Alluvium	Old Fluvial deposits poorly sorted, Silty yellowish clay with kankar mainly on uplands along water divides in interfluves.	Upper Pleistocene
Basement	-	Not encountered	-

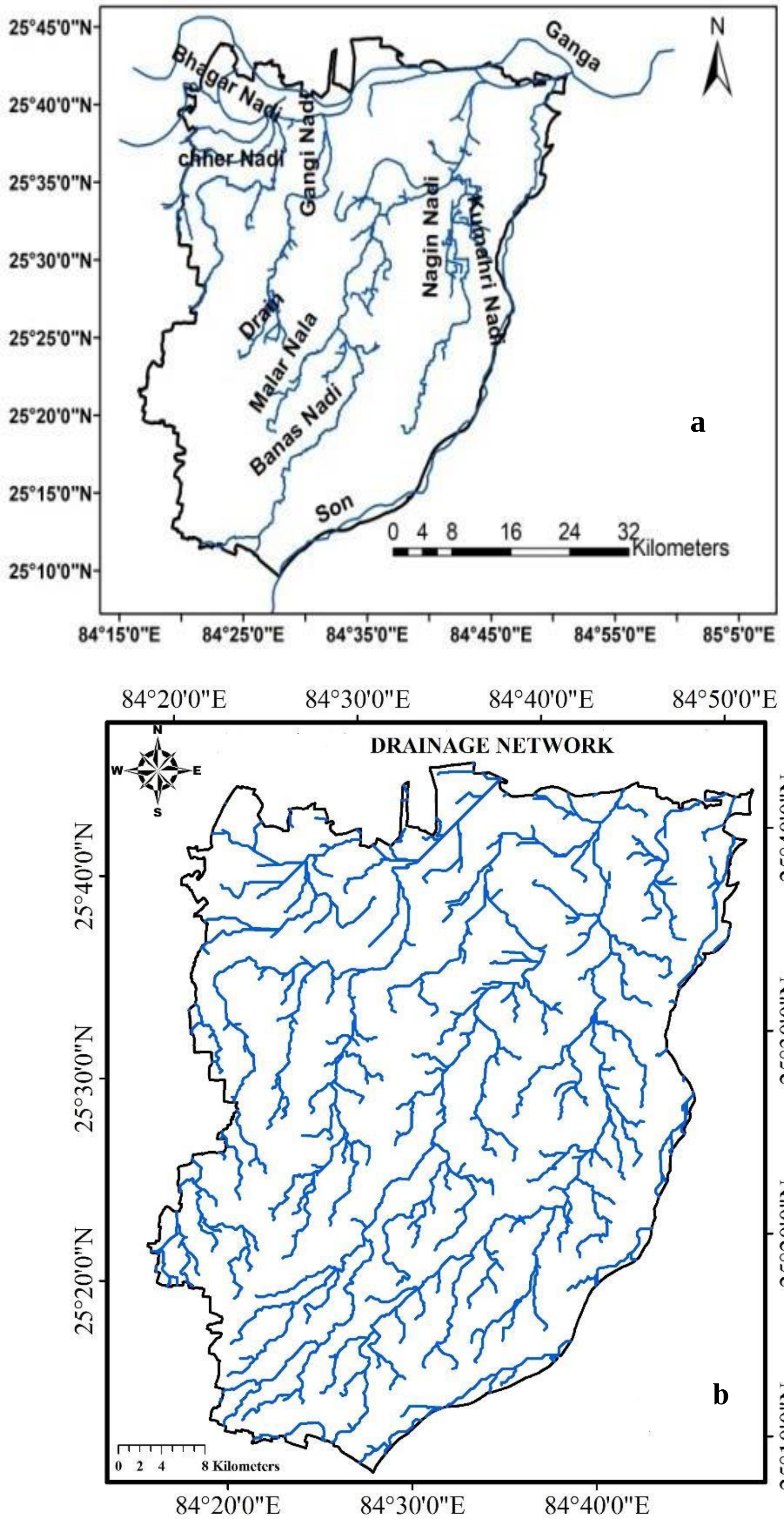


Figure 3.3: Drainage network map prepared based on (a) SoI Topo sheet (b) DEM

3.3 Hydrogeology

The district Bhojpur is occupied by Quaternary Alluvium which makes the potential aquifers. In the study area, the top layer of geological stratum (within 30 m bgl) is an aquitard, which supports dug wells and shallow hand pumps. In fact, it works as an unconfined aquifer. From 30 m to approx. 100 m bgl, medium to coarse sand forms the aquifer and after that, a thick layer (20-30 m) of clay is present. The deeper aquifers (> 130 m bgl) are under either semi-confined or confined conditions which sustain the deep wells in the area. The transmissibility varies from 4749 m^2/day to 15886 m^2/day while the storativity varies within 0.067 to 0.4×10^{-4} using pumping test/aquifer test (CGWB, 2013). In the study area the discharge varies between 150 to 200 m^3/hr with drawdown ranges between 3 and 10 m. The groundwater level data was collected from the Central Ground Water Board (CGWB) and spatial behavior of water levels along with flow direction has been studied for the Bhojpur district. The depth to water level in pre-monsoon season (year 2018) varies from 3.0 to 9.0 m bgl with minimum and maximum values observed in south western part and north eastern part. The hydraulic gradient indicated groundwater movement towards the river Ganga (Fig. 3.4). The fluctuation of groundwater level can be noticed between pre and post monsoon season (Fig. 3.5 has been shown as a representative for a well hydrograph) which indicates that natural recharge is good in the area. However, there is no declining trend in recent years has been observed in most of thewells.

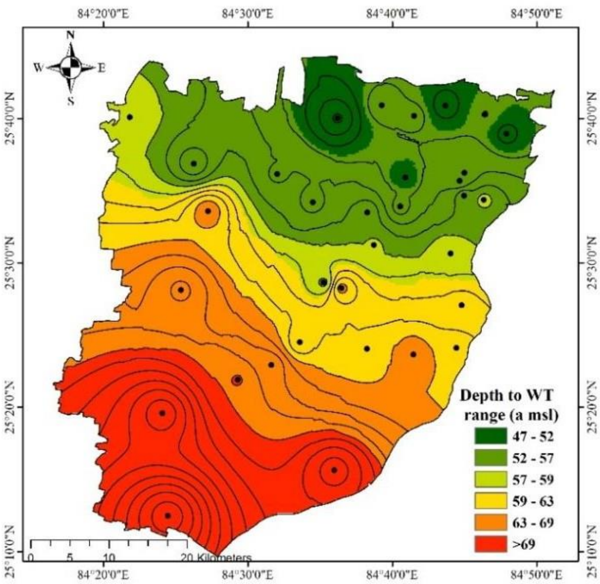


Figure 3.4: Groundwater contour map showing flow direction in the study area.

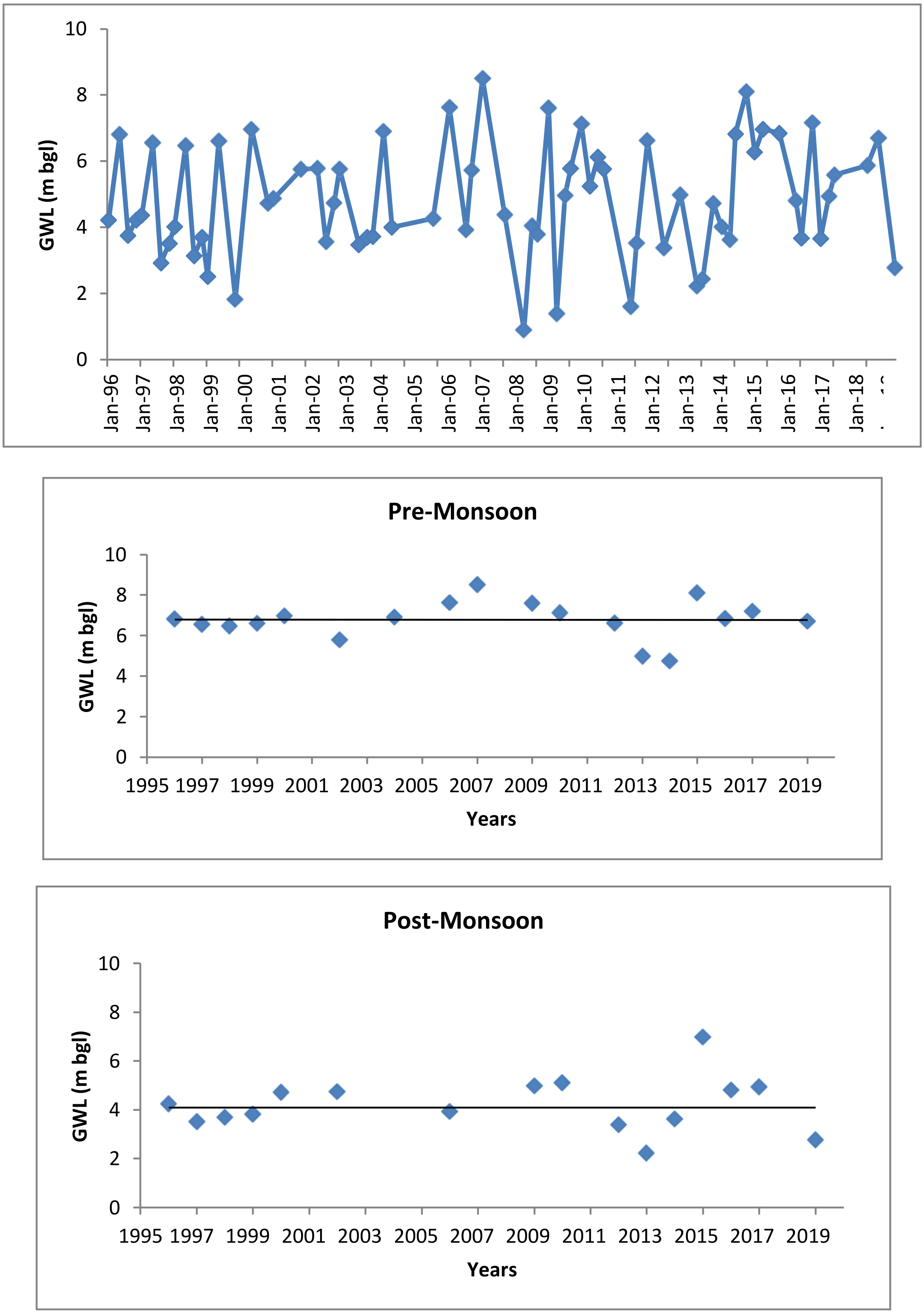


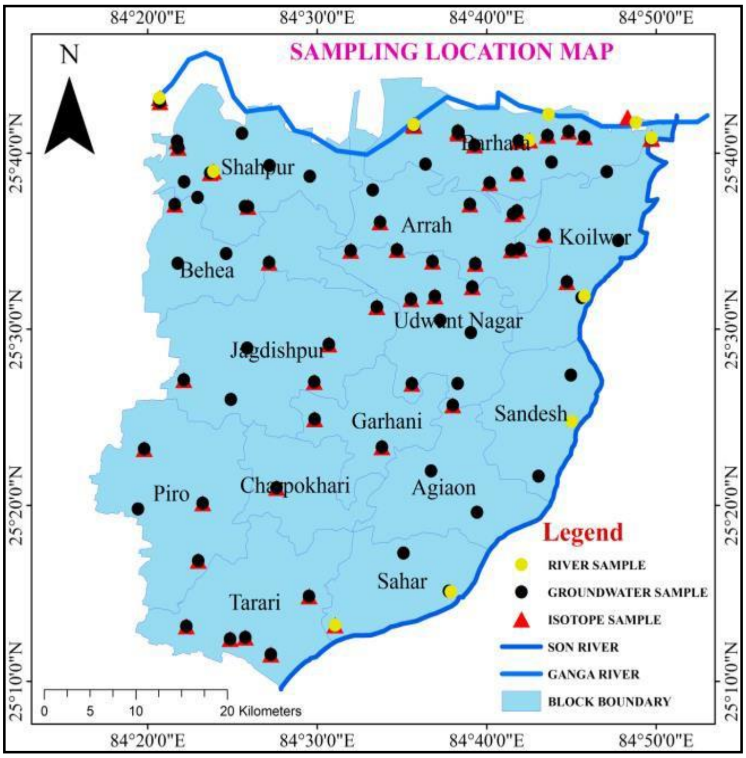
Figure 3.5: Variation of groundwater level at a monitoring station (Milki, Bhojpur) in the study area

4.0 METHODOLOGY

4.1 Water & Sediment Sampling

In order to understand the hydro geochemical evolution and arsenic occurrence in aquifer of the study area, the first step is to know the concentration and variation of chemical constituents. The first sampling campaign were conducted in Nov. 2018 (post-monsoon). The water samples were collected from different water sources such as ground water (hand pump and dug well) and surface water (Ganga and Son river). Entire district was divided into grid system i.e. northern part of the district along the Ganga river wasdivided 4x4 km grid pattern for dense sampling, whereas southern part of district was sampled using 8x8 km grid system. However due to approachability and practical limitation in the field the sampling pattern is not constantly uniform. In total, 94 representative water samples (85 groundwater and 9 rivers samples) were collected in polyethylene bottles along with their GPS coordinates during field visit for analysis of various physicochemical, trace metal and isotopic values. Based on results of first sampling analyses, focus was given on arsenic affected areas for detailed investigation. Forty-five groundwater samples were collected during second sampling compaign (May, 2019). These samples were repeated in Nov. 2019 for studying the seasonal variation. Figure 4.1 (a & b) shows the sampling location map of study area and details of samplingsites are given in Table 4.1 & 4.2.

The hand pumps were continuously purged for at least 15 minutes prior to the sampling, to ensure the groundwater to be sampled is representative of aquifer water. All thegroundwater samples were collected from the sources (private hand pump, depth ranges from 15 m to 80 m), which are being used extensively. Three samples set were taken fromeach site, one for chemical analysis (ions), another for isotope and trace metals analysis.In order to avoid any precipitation of trace elements, the samples collected for trace metals were acidified using HNO_3 to pH≈2 in the field. The sample's bottle was tightly sealed and brought to the laboratory for stable isotopic analysis to avoid any diffusive and evaporative losses.



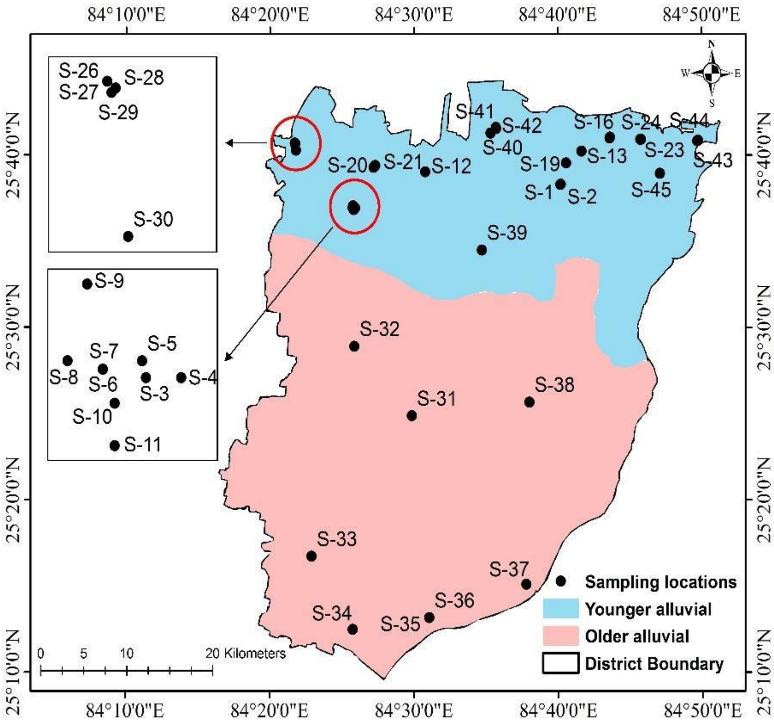


Figure 4.1: Water sampling locations map in the study area during (a) post monsoon (Nov. 2018) (b) pre-monsoon (May, 2019)

Table 4.1: Sampling site details of study area during post-monsoon (Nov. 2018)

S.No.	Location	Lat.	Long.	Block	Source
1	Dhanupura	25.5761	84.6989	Ara	HP
2	Moula bagh	25.5620	84.6555	Ara	HP
3	Bibiganj	25.5752	84.5786	Ara	HP
4	Gajrajpur	25.5745	84.5330	Udwantnagar	HP
5	Goda devi	25.6014	84.5618	Ara	HP
6	Bampali	25.5641	84.6134	Udwantnagar	HP
7	Dhobighat	25.5399	84.6526	Udwantnagar	HP
8	Dhanpura	25.5749	84.6909	Ara	HP
9	Mathulia	25.6092	84.6928	Ara	HP
10	Mathulia	25.6091	84.6927	Ara	HP
11	Barka lauhar	25.6475	84.6968	Barhara	HP
12	Bakhorapur	25.6119	84.6965	Ara	HP
13	Barahara	25.6833	84.7264	Barhara	HP
14	Barahara	25.6833	84.7264	Barhara	GR
15	Ekona	25.6871	84.7473	Barhara	HP
16	Ekona	25.6871	84.7473	Barhara	HP
17	Sirsiyan	25.6821	84.7627	Barhara	HP
18	Paiga	25.6384	84.6696	Barhara	HP
19	Shivpur	25.6742	84.6547	Barhara	HP
20	Englishpur	25.6562	84.6066	Barhara	HP
21	Jadopur	25.6183	84.6502	Ara	HP
22	Malther	25.5312	84.6158	Udwantnagar	HP
23	Asani	25.5285	84.5922	Udwantnagar	HP
24	Kaurva	25.5211	84.5587	Jagdishpur	HP
25	Khusma	25.4856	84.5115	Jagdishpur	HP
26	Baligaon	25.4149	84.4975	Garhani	HP
27	Tenduni	25.4335	84.4152	Jagdishpur	HP
28	Nayika Tolla	25.4821	84.4311	Jagdishpur	HP
29	Keshari	25.4520	84.3688	Jagdishpur	HP
30	Chakk Tolla	25.3867	84.3299	Piro	HP
31	Ojhawaliya	25.3353	84.3875	Piro	HP
32	AgionBazar	25.3299	84.3239	Piro	HP
33	Nagri	25.3500	84.4600	Charpokhari	HP
34	Benuva Tolla	25.3884	84.5637	Garhani	HP
35	Ahdhrohara	25.4484	84.5932	Udwantnagar	HP
36	Udwantnagar	25.5086	84.6211	Udwantnagar	HP
37	Anhari	25.2198	84.5176	Sahar	SR
38	Anhari	25.2198	84.5176	Sahar	HP
39	Khutar	25.2473	84.4920	Tarari	HP
40	Bihta	25.1922	84.4544	Tarari	HP
41	Bahnuwa	25.2083	84.4293	Tarari	HP

S.No.	Location	Lat.	Long.	Block	Source
42	Tarari	25.2068	84.4143	Tarari	HP
43	Kharauha	25.2188	84.3713	Tarari	HP
44	Jethwah	25.2809	84.3831	Piro	HP
45	Khayamnagar	25.5896	84.7236	Koilwar	HP
46	Koilwar	25.5838	84.7961	Koilwar	HP
47	Manikpur	25.6490	84.7849	Koilwar	HP
48	Manikpur	25.6809	84.8289	Barhara	SR
49	Son River FP	25.6803	84.8281	Barhara	HP
50	Bahiyara	25.5314	84.7629	Koilwar	SR
51	Bahiyara	25.5300	84.7600	Koilwar	HP
52	Kundeshwar	25.6180	84.3600	Behea	HP
53	Suhiya	25.6493	84.3980	Shahpur	GR
54	Ishwerpura (S)	25.6778	84.3624	Shahpur	HP
55	Suhiya	25.6480	84.3948	Shahpur	HP
56	Suhiya	25.6479	84.3949	Shahpur	HP
57	Ishwerpura (H)	25.6778	84.3624	Shahpur	HP
58	Ishwerpura (F)	25.6719	84.3633	Shahpur	HP
59	SamariaOjha Patti	25.6162	84.4291	Shahpur	HP
60	SamariaOjha Patti	25.6158	84.4311	Shahpur	HP
61	SamariaOjha patti	25.6158	84.4320	Shahpur	HP
62	Narinpur	25.4501	84.4971	Jagdishpur	HP
63	Behea Bazar	25.5632	84.4527	Behea	HP
64	Ganj	25.5716	84.4105	Behea	HP
65	Jogibir	25.5624	84.3629	Behea	HP
66	Dumaria	25.6248	84.3825	Shahpur	HP
67	Sarna	25.6395	84.3692	Shahpur	HP
68	Chamarpur	25.6550	84.4532	Shahpur	HP
69	Rajapur	25.6447	84.4927	Shahpur	HP
70	Salempur	25.6317	84.5546	Ara	HP
71	Mauzampur	25.6937	84.5948	Barhara	GR
72	Mauzampur	25.6925	84.5951	Barhara	HP
73	Narbirpur	25.5448	84.7456	Koilwar	HP
74	Nasarathpur	25.4565	84.7495	Sandesh	HP
75	Son River	25.4126	84.7506	Sandesh	SR
76	Tirthkul	25.4126	84.7506	Sandesh	HP
77	AhmadChak Tola	25.3609	84.7176	Sandesh	HP
78	Karbasen Ka tola	25.3267	84.6573	Agiaon	HP
79	Sahar	25.2514	84.6315	Sahar	SR
80	Sahar	25.2520	84.6297	Sahar	HP
81	Ekwari	25.2881	84.5848	Sahar	HP
82	Chauriya	25.3658	84.6121	Agiaon	HP
83	Belaur	25.4486	84.6382	Udwantnagar	HP
84	Pipania	25.4968	84.6511	Udwantnagar	HP

S.No.	Location	Lat.	Long.	Block	Source
85	Bharara	25.6832	84.7265	Barhara	HP
86	Chhetni Ka Bag	25.6581	84.7305	Barhara	HP
87	Bhagwanpur	25.4281	84.6334	Agiaon	HP
88	Nakhnaam Tola	25.6788	84.7088	Barhara	GR
89	Nakhnaam Tola	25.6788	84.7088	Barhara	HP
90	Nakhnaam Tola	25.6781	84.6982	Barhara	HP
91	Ghaziapur	25.6867	84.6389	Barhara	HP
92	Ghaziapur	25.6854	84.6387	Barhara	HP
93	Ghaziapur	25.6873	84.6384	Barhara	HP
94	Damodarpur	25.6854	84.4260	Shahpur	HP

HP= Hand Pump, GR= Ganga River, SR= Son River

Table 4.2: Sampling locations in the study area during pre-monsoon (May, 2019).

S.No.	Site Code	Location	Lat.	Long.	Block	Source
1	B1	Paiga	25.64	84.67	Barhara	HP
2	B2	Paiga	25.64	84.67	Sahapur	HP
3	B3	Semaria Ojhapatti	25.62	84.43	Sahapur	HP
4	B4	Semaria Ojhapatti	25.62	84.43	Sahapur	HP
5	B5	Semaria Ojhapatti	25.62	84.43	Sahapur	HP
6	B6	Semaria Ojhapatti	25.62	84.43	Sahapur	HP
7	B7	Semaria Ojhapatti	25.62	84.43	Sahapur	HP
8	B8	Semaria Ojhapatti	25.62	84.43	Sahapur	HP
9	B9	Semaria Ojhapatti	25.62	84.43	Sahapur	HP
10	B10	Semaria Ojhapatti	25.62	84.43	Sahapur	HP
11	B11	Sahana/Mangla	25.61	84.43	Barahara	HP
12	B12	Sudarpur Barja	25.68	84.51	Barahara	HP
13	B13	Balaharpur	25.67	84.69	Barahara	HP
14	B14	Balaharpur	25.67	84.69	Barahara	HP
15	B15	Barahara	25.68	84.73	Barahara	HP
16	B16	Barahara	25.68	84.73	Barahara	HP
17	B17	Sirsiyan	25.68	84.76	Barahara	HP
18	B18	Sirsiyan	25.68	84.76	Barahara	HP
19	B19	Hazipur	25.66	84.68	Barahara	HP
20	B20	Chamarpur	25.65	84.45	Barahara	HP
21	B21	Chamarpur	25.66	84.46	Barahara	HP
22	B22	Suhiya	25.68	84.76	Sahapur	HP
23	B23	Suhiya	25.68	84.76	Sahapur	HP
24	B24	Suhiya	25.68	84.76	Sahapur	HP
25	B25	Ishwerpura	25.68	84.36	Sahapur	HP
26	B26	Ishwerpura	25.68	84.36	Sahapur	HP
27	B27	Ishwerpura	25.68	84.36	Sahapur	HP
28	B28	Ishwerpura	25.68	84.36	Sahapur	HP
29	B29	Ishwerpura	25.68	84.36	Sahapur	HP

S.No.	Site Code	Location	Lat.	Long.	Block	Source
30	B30	Ishwerpura	25.67	84.36	Sahapur	HP
31	B31	Baligaon	25.41	84.50	Jagdishpur	HP
32	B32	Naika tola	25.48	84.43	Jagdishpur	HP
33	B33	Jaithwar	25.28	84.38	Tarari	HP
34	B34	Bahnuwa	25.21	84.43	Tarari	HP
35	B35	Anhari	25.22	84.52	Sahar	HP
36	B36	Anhari	25.22	84.52	Sahar	HP
37	B37	Sahar	25.25	84.63	Sahar	HP
38	B38	Bhagawanpur	25.43	84.63	Jagdishpur	HP
39	B39	Bibiganj	25.58	84.58	Ara	HP
40	B40	Maulighat	25.69	84.59	Barahara	HP
41	B41	Maulighat	25.69	84.60	Barahara	HP
42	B42	Mauzampur	25.69	84.59	Barahara	HP
43	B43	Bindgaon	25.68	84.83	Koilwer	HP
44	B44	Bindgaon	25.68	84.83	Koilwer	HP
45	B45	Manikpur	25.65	84.78	Koilwer	HP

HP= Hand Pump, GR= Ganga River, SR= Son River

Apart from the water sampling, sediment samples were also collected while drilling of boreholes. Eight piezometers were constructed after identifying the drilling sites based on their geomorphological settings in the study area. Figure 4.2 showing the geographical locations of drilling sites and the details are given in Table 4.3. The piezometers were constructed using the local hand operated technique (Mahanta et. al. 2014) at varying depth to collect sediment samples from the shallow aquifer situated in newer and older alluvium zone of the study area. These constructed piezometers would be used for long term groundwater monitoring. Composite sediments samples (disturbed) coming out from the drilling pipe were collected depth wise from top to bottom at an interval of 10 feet or when there were any changes in lithology observed. The sediment samples were collected following the standard procedure and shipped to NIH laboratory for further analysis.

Table 4.3: Piezometer construction details in the study area.

Location	Site Code	Block	Depth (m)	Lat.	Long.
Samaria Ojhapatti	P-1	Sahapur	18.29	25.615774	84.430528
Samaria Ojhapatti	P-2	Sahapur	42.67	25.615640	84.430595
Ishwerpura	P-3	Sahapur	24.38	25.678257	84.357609
Suhiya	P-4	Sahapur	24.38	25.647930	84.395031
Mauzampur	P-5	Barhara	24.38	25.688590	84.588607
Sirsiyan	P-6	Barhara	24.38	25.682326	84.762628
Baligaon	P-7	Jagdishpur	24.38	25.416396	84.498108
Andhari	P-8	Sahar	24.38	25.678257	84.357609

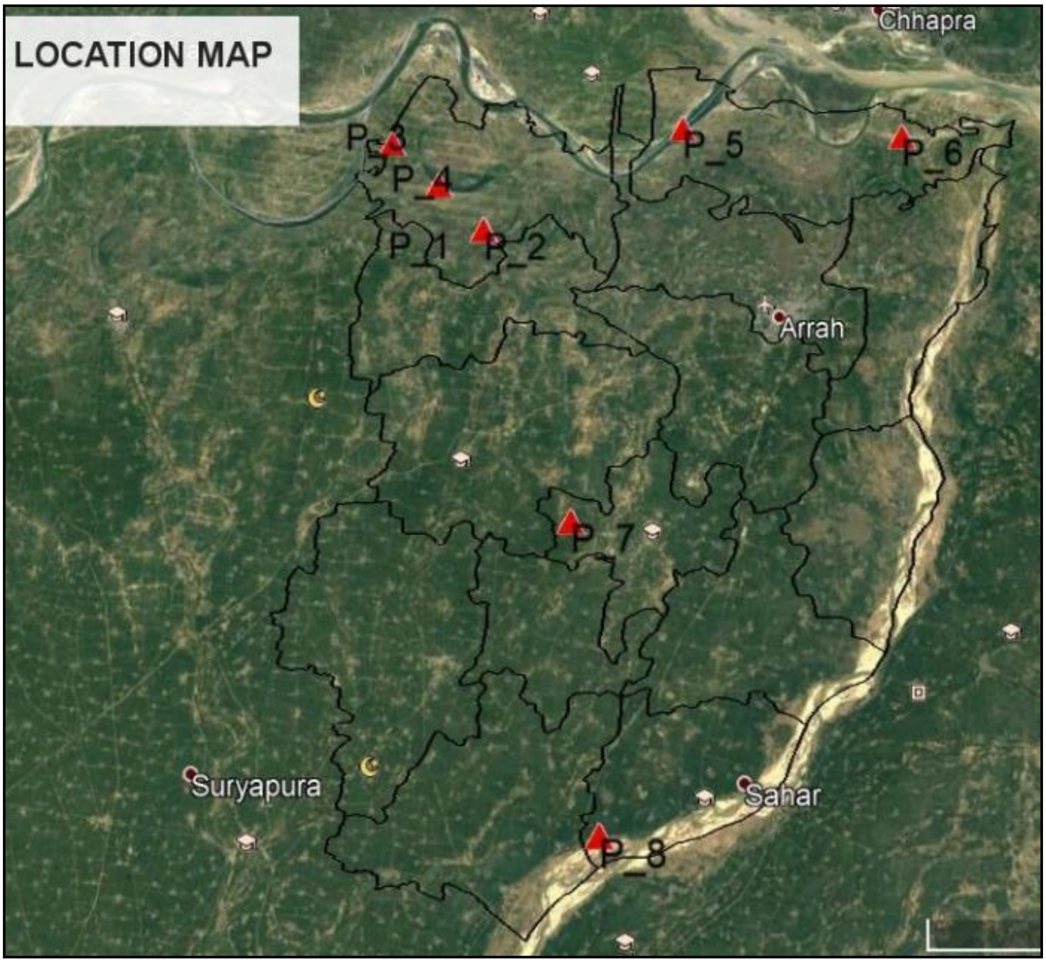


Figure 4.2: Location map of installed piezometers (P1, P2,… …P8) in the study area.

4.2 Methodology for water sample analysis

The samples were analysed as per Standard Methods for the Examination of Water and Wastewater (APHA, 2012; Jain and Bhatia, 1988). The details of analytical methods and equipment used in the study are given in Table 4.4. pH, electrical conductivity (EC), dissolved oxygen (DO), oxidation-reduction potential (ORP) were measured at site using multi-parameter analyzer (Hach, HQ 40 d).

The major cations (Ca^{2+}, Mg^{2+}, Na^{+} & K^{+}) and anions (Cl^{-}, SO_4^{2-}, NO_3^{-}, & F^{-}) in the samples were analyzed with the help of Ion Chromatography (IC, Dionex Series ICS- 5000). Ion chromatography is a form of liquid chromatography, in which ion exchange resins are employed to separate atomic and molecular ions for analysis. IC involves the retention of ions from the sample being retained based on ionic interactions. Quantification of cations and anions in the sample is based upon calibration curve of standard solutions of respective cations-anions. Bi-carbonate (HCO_3^{-}) was determined using titration method. Ionic balance was calculated and the error in the ionic balance of the samples was within

10%. Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES, Agilant 5110 VDV) was used for analysis of trace metals (As, Fe, Mn, Zn, Cu, Cr, Cd, Ni, Pb). The operational conditions were adjusted in accordance with the manufacture's guidelines to yield optimal determination.

Table 4.4: Analytical methods and equipment used for water samples analysis

Sr. No.	**Parameter**	**Method**	**Equipment Used**
Water Chemistry Analysis			
A.	**Physico-chemical (Major Ions)**		
1	pH	Electrometric	pH meter – Hach
2	Electrical Conductivity	Electrometric	Conductivity meter – Hach
3	Bicarbonate	Titration	Volumetric glassware
4	Calcium	Conductivity Method	Ion Chromatography
5	Magnesium		
6	Sodium		
7	Potassium		
8	Chloride		
9	Fluoride		
10	Nitrate		
11	Sulfate		
12	Ammonia		
B.	**Trace/Heavy Metals**		
13	Arsenic	Spectrometry Method	ICP-OES
14	Cobalt		
15	Cadmium		
16	Total Chromium		
17	Copper		
18	Zinc		
19	Iron		
20	Aluminum		
21	Manganese		
22	Nickel		
23	Lead		

4.3 Methodology for sediment sample analysis

The soil particle size distribution was analyzed using sieve shaker and Mastersizer particle size analyzer (Malvern Mastersizer 2000 E). The soil particle having size of morethan 75 µm was processed by sieve analysis whereas the soil particles passing through 75 µm sieve was measure through Mastersizer. Sodium hexa-meta phosphate was used asdispersing agent to disperse any aggregrate. The Mastersizer continuously pumps a portion of the soil suspension through a gap between two glass lenses fitted in the instrument. The size of the particles passing between the lenses is measured by the scattering pattern of the laser, as it diffracts off the particles, by application of the Fraunhofer model, and using Mie theory (Malvern Instruments, 2004). The calculated percentage of sand, silt and clay in a soil sample was used in determining textural classification using textural triangle of United State Department of Agriculture (USDA). The ICP-OES was used for determining trace metals in processed sediment samples. The Multiwave PRO microwave reaction system was used to digest soil samples for carrying out chemical analysis of these soil samples. The X-ray diffractometer (Bruker D8 Advance), IIT Roorkee was used for mineralogical study. The data was processes through "Xpert High Score" software for mineralogical phases identification. The major and minor oxides were determined by XRF (Bruker S4 Pioneer). The details of method and equipment used for sediment characterization are given in Table 4.5.

Table 4.5: Analytical methods and equipment used for sediment samples analysis

Sr. No.	Parameter	Method	Equipment Used
1	Grain Size Analysis	Sieve & Laser diffraction method	Malvern Instruments
2	All trace metals including As	Spectrometry Method	ICP-OES
3	Minerals (major and minor mineral)	XRD Technology	Bruker S4 Pioneer
4	Major & minoroxides	XRF Technology	D8 Advance (Bruker) X-ray diffractometer
5	Elemental composition	Scanning Electron Microscopy	FE-SEM

4.4 Methodology for column experiment

This study used the batch and column leaching tests to investigate and understand the arsenic leaching processes from sediment. The toxicity characteristic leaching procedure (TCLP) has been widely used to analyze trace metals leaching characteristic from contaminated soils (Sun et al., 2006; Yang et al., 2014; Houben et al.,2013, Li et al., 2017). For the batch and column experiment contaminated soil samples (Soil samples collected from at depth 40 ft while drilling from Simaria Ojha Patti village). For the batchexperiment, three grams of soil sample (<2 mm) was mixed with 30 mL of distill water that was adjusted to different pH values (6, 6.5, 7, 7.5, 8 and 8.5) by adding either hydrochloric acid (HCl) or sodium hydroxide (NaOH). The mixed samples were poured into an acid-rinsed 50-mL centrifuge tube. The slurry was shaken for 8 days at room temperature and atmospheric pressure using a reciprocating horizontal shaker (100 rpm). The samples were taken daily and were filtered through a 0.45-μm membrane Filter and preserved with HNO_3. Finally, the concentration of the leached heavy metals was measured using ICP-OES. The column experiment was also performed for 15 days and the column was fitted with an up-flow system with flow rate of 2ml/min. The column was fabricated with acrylic glass having dia 10 cm and height 40 cm as per design recommended by USEPA. The details of the column test are provided in Figure 4.3.

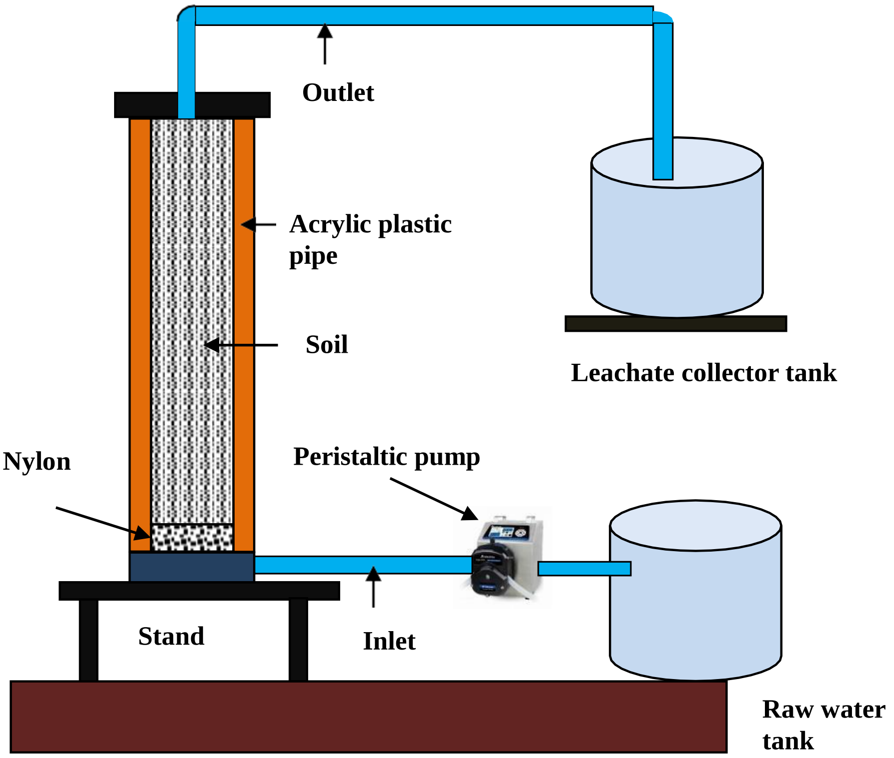


Figure 4.3: Schematic diagram of a laboratory based column experimental set-up.

5.0. RESULTS AND DISCUSSIONS

5.1 Geochemical Characteristics of Groundwater

Geochemical properties of groundwater play a significant role in determining its uses for different purposes. The water samples collected during different phases were analyzed for pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Sodium (Na^+), Potassium (K^+), Calcium(Ca^{++}), Magnesium (Mg^{++}), Bicarbonate (HCO_3^-), Sulphate (SO_4^{2-}), Nitrate (NO_3^-), Chloride (Cl^-) and trace metals (As, Cr, Cu, Co, Cd, Ni, Mn, Fe and Zn). The statistical summaries result and the location-wise analytical results for major ions are presented in Table 5.1, Table 5.2 and Table 5.3 respectively.

5.1.1 pH, EC and TDS

pH is one of the most important parameters in water chemistry and is defined as log[H^+]. It is measured as intensity of acidity or alkalinity on a scale ranging from 0-14. BIS (2012) has prescribed pH value in the range of 6.5 to 8.5 for drinking water purpose. The pH of the water samples of study area during post monsoon (Nov. 2019) varies from 7.0 (Anhari) to 8.4 (Dhanpura) (mean 7.8) for groundwater, 7.8 to 8.8 (mean: 8.3) for Ganga river and 7.5 to 8.7 (mean: 8.3) for Son river, respectively (Table 5.1). Whereas pH variesfrom 6.9 to 8.2 with an average value of 7.5 in GW samples of arsenic affected areas (Table 5.1). Figure 5.1 (a & b) shows the spatial distribution and bar chart of pHrespectively for post monsoon and pre-monsoon seasons in the study area and results reveal that overall groundwater samples are alkaline in nature and most of the samples is having pH in the range of 7.5-8.0.

EC is a measure of the ability of an aqueous solution to carry an electric current. In the study area EC values during post monsoon varies from 240 to 1635 µS/cm (mean 694 µS/cm) for groundwater, 300 to 560 µS/cm (mean: 449 µS/cm) for Ganga river and 190 to 240 µS/cm (mean: 220µS/cm) for Son river, whereas in groundwater samples during pre-monsoon EC varies from 383 to 1415 µS/cm with an average value of 708 µS/cm in groundwater (Table 5.1). Figure 5.2 (a &b) shows the spatial distribution and bar chart of EC for post monsoon and pre-monsoon seasons in the study area. The results show that groundwater is fresh in nature and suitable for drinking and irrigation uses.

Table 5.1: Statistical evaluation of water quality parameters in post monsoons season (entire district) and pre-monsoon season (arsenic affected areas of the study area) (all conc. in mg/L, except EC in µS/cm)

PARAMETERS			pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	NO_3^{-}	F^{-}
BIS limit		Acceptable	6.5-8.5	-	500	75	30	-	-	200	250	200	45	1
		Permissible	NR	-	2000	200	100	-	-	600	1000	400	NR*	1.5
Water Sources	GW	MIN.	7.0	240	271	32	8.1	0.3	0.5	186	0.6	0.1	ND	ND
		MAX.	8.4	1635	1126	101	71.6	137	32.5	443	183.0	154.0	70.2	1.20
		AVG.	7.8	694	496	61.7	21.7	34.7	4.0	316	29.6	18.9	7.9	0.32
		S.D.	0.3	272	141	17.8	9.8	25.9	4.6	58	39.1	27.8	13.1	0.25
	Ganga	MIN.	7.8	300	253	33.3	8.68	13.88	3.5	174	6.5	6.4	ND	0.10
		MAX.	8.8	560	414	51.7	17.95	31	5.2	284	21.9	20.8	0.4	0.29
		AVG.	8.3	449	337	40.5	14.33	21.91	4.22	229	13.5	12.5	0.1	0.18
		S.D.	0.4	111	67	8.8	4.03	7.426	0.8	50	7.2	6.2	0.2	0.08
	Son	MIN.	7.5	190	174	22.9	6.0	8.6	2.1	121	4.1	7.2	ND	0.20
		MAX.	8.7	240	212	30.8	8.19	10.75	2.48	150	5.9	8.5	0.5	0.28
		AVG.	8.3	220	195	26.96	7.06	9.54	2.21	135	5.0	7.9	0.1	0.24
		S.D.	0.5	21	18	3.37	0.89	0.87	0.16	13	0.7	0.5	0.2	0.04
					Pre-monsoon season GW samples' analytical results									
	GW	MIN.	6.9	383	245.1	41.2	11.8	9.8	0.4	240.1	1.2	3.8	ND	0.10
		MAX.	8.2	1415	905.6	139.9	65.0	72.7	70.4	706.6	91.2	43.3	29.4	0.72
		AVG.	7.5	703	450.4	76.4	27.1	27.9	4.4	423.1	17.6	11.1	6.1	0.60
		S.D.	0.34	206	131.96	24.15	12.28	13.02	10.55	112.52	19.52	8.83	6.96	0.16

GW-Groundwater, ND-Not Detected, NR- No Relaxation

Table 5.2: Physico-chemical characteristics of water samples during post-monsoon (all conc. in mg/L except pH and EC in µS/cm).

S.No.	Sample Code	Location	Source	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{-}	NO_3^{-}	F^{-}
1	ARA_1	Dhanupura	HP	8.40	780	410	60.8	11.2	16.3	2.5	310.5	5.5	2.9	ND	0.18
2	ARA_2	Moula Bagh	HP	7.70	780	478	67.6	17.2	33.4	1.9	285.6	42.6	19.3	9.60	0.29
3	ARA_3	Bibiganj	HP	8.10	540	437	65.7	14.1	20.9	2.7	306.2	11.7	15.2	ND	0.24
4	ARA_4	Gajrajpur	HP	7.90	1030	604	41.7	27.8	68.2	4.0	388.1	38.6	35.6	ND	0.11
5	ARA_5	Goda devi	HP	8.10	610	457	57.8	17.4	21.8	4.2	351.0	3.5	1.0	ND	0.15
6	ARA_6	Bampali	HP	7.60	640	414	50.2	20.0	22.4	2.4	295.9	12.5	10.0	ND	0.22
7	ARA_7	Dhobi ghat	HP	7.80	500	357	56.8	8.1	26.9	1.8	223.6	23.9	7.7	8.18	0.15
8	ARA_8	Dhanpura	HP	7.60	580	337	39.7	14.0	22.1	1.2	240.5	12.6	6.6	0.08	0.34
9	ARA_9	Mathulia	HP	7.90	660	443	68.4	17.5	23.5	4.2	275.5	32.1	21.2	0.08	0.22
10	ARA_10	Mathulia	HP	7.60	1280	722	97.0	25.1	66.7	18.3	276.4	135.2	102.5	ND	0.15
11	ARA_11	Barka lauhar	HP	7.90	1210	648	38.4	19.8	45.7	32.5	351.5	51.2	55.8	70.20	0.24
12	ARA_12	Bakhorapur	HP	8.00	510	389	49.7	18.6	10.5	4.8	282.2	7.7	11.2	3.82	0.17
13	ARA_13	Barahara	HP	7.50	540	473	67.9	16.3	16.2	3.1	363.2	3.9	2.2	0.04	0.17
14	ARA_14	Barahara	GR	8.10	300	253	33.6	8.7	13.9	3.6	174.4	8.7	9.6	0.02	0.29
15	ARA_15	Ekona	HP	7.50	830	513	56.4	29.9	34.5	4.5	282.8	39.8	47.3	17.50	0.16
16	ARA_16	Ekona	HP	7.80	600	422	54.3	15.5	24.5	3.4	310.3	7.1	6.2	0.06	0.20

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Location	Source	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^-	NO_3^-	F^-
17	ARA_17	Sirsiyan	HP	7.50	690	588	98.1	22.7	24.4	3.3	435.3	3.7	0.4	0.06	0.20
18	ARA_18	Paiga	HP	7.70	520	473	77.0	17.0	22.7	3.0	348.2	4.5	0.3	0.05	0.23
19	ARA_19	Shivpur	HP	7.90	600	424	61.4	15.1	18.7	6.6	264.5	18.4	28.4	9.84	0.85
20	ARA_20	Englishpur	HP	7.60	540	480	68.6	21.2	26.6	1.9	359.0	1.6	0.4	0.04	0.41
21	ARA_21	Jadopur	HP	7.90	360	288	51.3	9.6	8.4	2.2	210.6	2.6	2.6	0.00	0.40
22	ARA_22	Malther	HP	7.70	1300	800	73.1	27.3	137.1	1.6	327.4	177.0	41.1	14.49	0.33
23	ARA_23	Asani	HP	7.40	570	479	66.1	17.8	34.4	1.7	348.7	7.6	2.0	0.68	0.26
24	ARA_24	Kaurva	HP	7.40	670	439	54.8	18.7	35.9	1.4	277.4	31.8	16.1	2.59	0.24
25	ARA_25	Khusma	HP	8.00	590	377	34.6	23.3	26.1	1.0	283.4	6.4	1.7	0.00	0.45
26	ARA_26	Baligaon	HP	7.50	540	442	59.5	20.1	20.4	3.2	299.7	15.6	11.2	11.87	0.47
27	ARA_27	Tenduni	HP	7.60	490	373	62.5	10.8	19.4	3.0	242.4	21.0	12.6	1.28	0.28
28	ARA_28	Nayika Tolla	HP	7.30	350	271	32.3	19.4	8.8	0.5	185.8	4.2	5.5	14.27	0.37
29	ARA_29	Keshari	HP	7.80	380	334	46.7	12.8	17.9	0.8	237.7	6.2	5.1	5.25	0.53
30	ARA_30	Chakk Tolla	HP	7.90	610	563	70.0	26.0	33.5	3.8	411.3	9.8	2.7	5.01	0.49
31	ARA_31	Ojhawaliya	HP	7.30	330	498	51.9	24.7	45.2	1.1	297.6	47.1	24.2	6.05	0.40
32	ARA_32	AgionBazar	HP	7.90	550	429	44.9	16.6	37.7	1.1	308.0	13.4	5.8	0.93	0.48
33	ARA_33	Nagri	HP	7.70	710	617	94.8	25.4	31.6	2.1	408.3	27.5	16.7	10.36	0.30
34	ARA_34	Benuva Tolla	HP	7.70	860	682	87.6	24.0	82.7	1.5	349.3	79.6	40.7	15.46	0.54
35	ARA_35	Ahdhrohara	HP	7.90	520	440	64.5	20.8	23.7	1.6	321.8	3.1	2.2	1.48	0.34
36	ARA_36	Udwantnagar	HP	7.80	1320	629	41.5	25.2	101.7	1.2	326.3	81.1	29.6	21.14	0.62

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Location	Source	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^-	NO_3^-	F^-
37	ARA_37	Anhari	SR	7.50	240	210	29.0	8.2	10.7	2.5	145.8	5.9	8.0	0.02	0.28
38	ARA_38	Anhari	HP	7.00	430	380	50.2	19.4	18.0	1.0	276.3	4.4	5.3	4.58	0.53
39	ARA_39	Khutar	HP	7.30	450	398	60.8	14.7	13.4	1.6	282.5	12.4	6.9	5.11	0.43
40	ARA_40	Bihta	HP	7.30	560	538	71.1	18.5	29.6	5.9	383.1	13.3	8.2	7.56	0.35
41	ARA_41	Bahnuwa	HP	7.50	540	466	89.1	15.3	18.3	1.3	292.3	22.6	14.1	12.66	0.33
42	ARA_42	Tarari	HP	7.50	890	625	89.5	21.9	64.8	1.0	286.8	92.8	37.8	29.52	0.34
43	ARA_43	Kharauha	HP	7.70	710	518	56.9	15.6	51.0	0.8	340.1	28.2	15.7	9.17	0.50
44	ARA_44	Jethwah	HP	7.60	370	339	52.3	9.3	16.4	1.2	255.8	2.1	1.0	0.47	0.32
45	ARA_45	Khayamnagar	HP	8.10	500	317	36.2	16.1	19.9	1.7	232.0	3.3	6.8	0.00	0.37
46	ARA_46	Koilwar	HP	7.70	640	388	34.8	18.2	40.7	2.1	271.6	17.1	3.2	0.00	0.21
47	ARA_47	Manikpur	HP	7.70	520	431	69.1	14.7	9.9	2.0	327.9	5.9	1.5	0.00	0.14
48	ARA_48	Manikpur	SR	8.50	240	212	30.8	7.4	9.7	2.1	149.9	5.0	7.2	0.02	0.26
49	ARA_49	Son River FP	HP	7.40	790	409	47.7	25.4	12.4	4.5	307.4	5.9	1.6	0.00	0.21
50	ARA_50	Bahiyara	SR	8.40	220	199	28.1	7.4	9.8	2.1	137.0	5.3	8.0	0.52	0.24
51	ARA_51	Bahiyara	HP	8.10	240	343	55.9	12.0	13.6	1.3	251.0	4.0	4.7	0.02	0.44
52	ARA_52	Kundeshwar	HP	7.60	960	511	57.7	21.9	55.2	2.6	256.0	26.5	48.1	42.34	0.16
53	ARA_53	Suhiya	GR	8.40	560	414	51.7	18.0	24.4	5.2	284.5	16.9	13.2	0.09	0.13
54	ARA_54	Ishwerpura (S)	HP	8.00	1120	754	80.2	53.8	58.3	5.4	396.2	97.0	57.8	4.51	0.10
55	ARA_55	Suhiya	HP	7.90	640	542	94.0	18.2	20.2	3.4	340.0	35.1	30.7	0.00	0.14
56	ARA_56	Suhiya	HP	7.80	630	386	48.2	16.3	25.7	6.7	245.0	21.6	21.8	0.57	0.09

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Location	Source	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^-	NO_3^-	F^-
57	ARA_57	Ishwerpura (Home)	HP	7.60	1180	691	74.6	45.8	49.0	4.5	378.9	82.4	48.6	6.37	0.08
58	ARA_58	Ishwerpura (Field)	HP	7.70	1140	506	51.3	28.3	33.9	3.7	383.1	5.0	0.3	0.13	0.11
59	ARA_59	Samaria OjhaPatti	HP	7.90	770	491	57.6	22.6	26.3	2.4	352.7	25.9	0.2	2.91	0.46
60	ARA_60	Samaria OjhaPatti	HP	8.10	540	347	38.4	17.5	23.7	2.2	255.0	6.3	3.0	0.00	0.18
61	ARA_61	Samaria Ojha patti	HP	7.90	510	525	82.0	18.5	21.9	2.2	391.9	5.9	1.5	0.41	0.21
62	ARA_62	Narinpur	HP	8.20	880	666	63.4	21.5	75.4	5.4	413.3	45.1	19.0	22.30	0.29
63	ARA_63	Behea Bazar	HP	7.90	620	613	89.1	34.2	35.9	1.5	355.6	57.2	14.5	23.99	0.53
64	ARA_64	Ganj	HP	7.70	620	543	91.4	12.7	44.0	1.9	323.8	37.5	14.8	16.48	0.20
65	ARA_65	Jogibir	HP	8.10	660	412	34.5	13.9	53.3	1.6	262.0	22.3	8.2	15.95	0.35
66	ARA_66	Dumaria	HP	7.90	600	357	42.0	16.8	20.6	4.0	234.2	17.2	21.3	0.05	0.20
67	ARA_69	Sarna	HP	7.90	730	501	35.6	16.8	0.3	2.0	329.4	10.4	96.9	9.10	0.04
68	ARA_70	Chamarpur	HP	8.10	620	539	84.7	22.4	25.8	2.9	388.0	10.9	0.1	4.20	0.18
69	ARA_71	Rajapur	HP	7.90	1240	612	49.4	27.8	72.1	28.4	295.2	93.4	38.7	0.18	0.60
70	ARA_72	Salempur	HP	8.20	550	471	56.5	17.8	35.7	2.9	347.7	3.2	5.1	1.50	0.25
71	ARA_73	Mauzampur	GR	8.80	440	328	33.3	14.4	31.0	4.5	201.3	21.9	20.8	0.00	0.20
72	ARA_74	Mauzampur	HP	7.50	880	573	57.5	36.9	25.6	1.6	434.2	7.9	7.0	1.00	0.00
73	ARA_75	Narbirpur	HP	7.80	680	450	64.3	16.8	28.7	1.7	272.2	25.9	16.0	23.50	0.25
74	ARA_76	Nasarathpur	HP	8.00	650	525	69.3	23.2	27.8	1.7	352.8	15.0	9.5	24.90	0.34
75	ARA_77	Son River	SR	8.70	210	178	24.0	6.3	8.8	2.2	123.2	4.8	8.0	0.00	0.20
76	ARA_78	Tirthkul/Sandesh	HP	7.90	640	514	68.0	29.6	24.5	1.0	362.3	6.9	10.0	10.50	0.90

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Location	Source	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^-	NO_3^-	F^-
77	ARA_79	Ahmad Chak Tola	HP	8.00	430	387	62.9	12.4	22.0	1.2	280.6	3.5	3.3	0.90	0.40
78	ARA_80	Karbasen Ka tola	HP	8.10	760	639	96.0	32.5	35.4	1.3	397.7	47.2	28.0	0.00	0.40
79	ARA_81	Sahar	SR	8.50	190	174	22.9	6.0	8.6	2.1	121.3	4.1	8.5	0.00	0.20
80	ARA_82	Sahar	HP	7.90	790	450	56.0	25.8	26.0	0.8	252.7	47.6	16.0	23.90	0.40
81	ARA_83	Ekwari	HP	8.00	510	439	61.8	15.1	21.3	1.1	319.2	12.9	4.9	2.50	0.40
82	ARA_84	Chauriya	HP	8.20	680	455	32.0	30.6	36.7	1.2	317.2	31.8	5.1	0.00	0.30
83	ARA_85	Belaur	HP	8.00	410	535	61.3	19.5	40.5	1.7	396.5	10.4	3.4	1.00	0.30
84	ARA_86	Pipania	HP	8.00	550	444	42.0	21.3	38.4	1.5	335.5	2.9	1.9	0.00	0.40
85	ARA_87	Bharara	HP	7.10	733	586	67.0	20.6	32.8	9.0	439.2	11.5	5.0	0.00	0.30
86	ARA_94	Chhetni Ka Bag	HP	7.50	527	376	58.7	11.6	10.5	1.9	290.4	2.9	0.2	0.00	0.20
87	ARA_95	Bhagwanpur	HP	7.80	451	388	45.4	26.0	15.4	0.6	285.5	0.6	7.0	6.90	0.50
88	ARA_104	Nakhnaam Tola	GR	7.80	495	353	43.3	16.3	18.4	3.5	257.4	6.5	6.4	0.40	0.10
89	ARA_105	Nakhnaam Tola	HP	7.60	544	371	49.1	21.2	12.0	4.4	269.6	6.7	6.7	0.00	0.12
90	ARA_106	Nakhnaam Tola	HP	7.60	572	370	46.1	17.6	11.9	3.1	284.3	3.2	4.0	0.00	0.00
91	ARA_107	Ghaziapur	HP	7.50	734	489	67.9	28.6	25.6	4.2	319.6	25.3	17.6	0.00	0.10
92	ARA_108	Ghaziapur	HP	7.30	1635	937	100.6	49.2	116.2	10.0	273.3	183.0	139.5	64.90	0.00
93	ARA_109	Ghaziapur	HP	7.50	1550	1126	98.6	71.6	136.0	22.4	443.5	166.0	154.0	32.50	0.00
94	ARA_110	Damodarpur	HP	7.60	1014	651	78.5	34.8	63.9	2.0	304.4	101.7	36.4	26.98	1.20

HP= Hand Pump, GR= Ganga River, SR= Son River

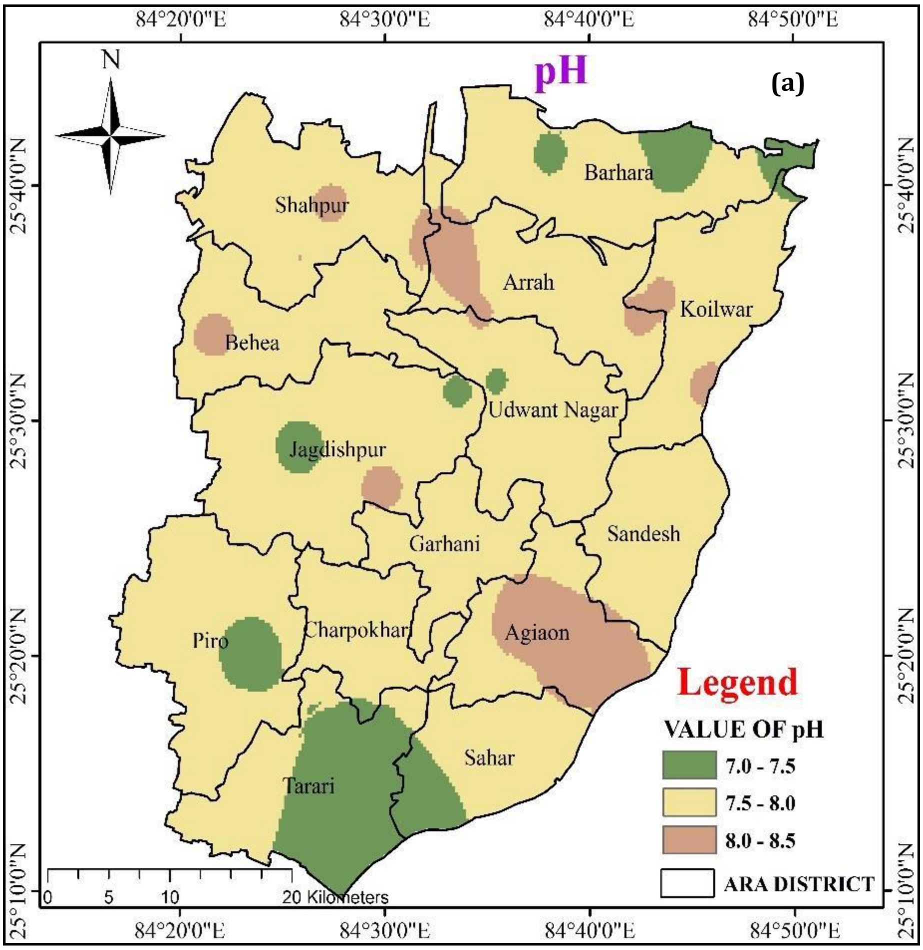
Table 5.3: Physico-chemical characteristics of water samples during pre-monsoon (all conc. in mg/L except pH & EC in µS/cm).

S.No.	Sample Code	Location	Source	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^-	NO_3^-	F^-
1	B1	Paiga	HP	7.0	592	448	78	21	22	4.25	0.51	12.76	305	5	0.5
2	B2	Paiga	HP	6.9	956	565	80	20	25	2.47	0.58	7.37	424	6	ND
3	B3	Semaria Ojhapatti	HP	7.0	640	469	50	21	26	1.81	0.46	11.00	352	7	ND
4	B4	Semaria Ojhapatti	HP	7.1	567	460	77	19	22	1.68	0.43	3.73	330	5	1.2
5	B5	Semaria Ojhapatti	HP	7.1	636	475	60	22	29	1.65	0.20	9.36	347	6	ND
6	B6	Semaria Ojhapatti	HP	7.2	691	572	76	26	29	2.13	0.23	14.45	420	4	ND
7	B7	Semaria Ojhapatti	HP	7.2	598	529	62	19	29	1.44	0.22	6.44	404	7	ND
8	B8	Semaria Ojhapatti	HP	7.1	979	773	117	38	44	2.46	ND	48.35	515	4	3.6
9	B9	Semaria Ojhapatti	HP	7.6	498	469	53	16	31	1.77	0.17	1.22	359	7	ND
10	B10	Semaria Ojhapatti	HP	7.3	622	460	62	20	27	1.67	0.17	12.53	329	7	ND
11	B11	Sahana (Mangla)	HP	7.3	665	541	64	24	32	1.95	0.21	6.29	406	5	ND
12	B12	Sudarpur Barja	HP	7.3	470	419	53	17	10	2.49	0.26	1.63	328	7	ND
13	B13	Balaharpur	HP	7.7	571	487	44	13	21	45.0	0.22	11.38	302	21	4.5
14	B14	Balaharpur	HP	7.5	456	376	62	12	11	6.84	0.32	6.33	264	14	ND
15	B15	Barahara	HP	8.0	540	456	49	23	40	5.87	0.23	21.98	308	7	0.4
16	B16	Barahara	HP	7.6	541	487	80	21	21	2.61	0.07	4.40	349	9	ND
17	B17	Sirsiyan	HP	7.2	772	606	93	27	27	2.47	0.16	3.51	446	7	ND
18	B18	Sirsiyan	HP	7.5	680	566	75	27	23	2.75	0.04	2.86	428	6	ND
19	B19	Hazipur	HP	7.8	383	342	58	12	12	2.91	0.17	5.89	240	11	ND
20	B20	Chamarpur	HP	7.2	732	646	95	28	31	2.49	0.16	11.63	471	5	ND
21	B21	Chamarpur	HP	7.9	801	680	77	29	37	3.03	ND	22.45	506	5	0.9
22	B22	Sirhiya	HP	7.4	692	490	78	19	23	6.60	ND	5.40	351	5	ND
23	B23	Sirhiya	HP	7.5	724	600	102	22	27	3.08	ND	41.27	372	31	ND
24	B24	Sirsiya	HP	7.5	560	415	63	19	17	3.70	ND	16.15	283	12	0.4

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Location	Source	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	Cl^-	SO_4^-	NO_3^-	F^-
25	B25	Ishwerpura	HP	7.5	1050	1034	140	65	73	6.61	ND	62.09	618	40	29.4
26	B26	Ishwerpura	HP	7.9	629	469	65	24	17	2.81	ND	1.74	350	7	ND
27	B27	Ishwerpura	HP	7.7	810	768	110	48	30	3.63	ND	22.79	531	14	6.4
28	B28	Ishwerpura	HP	7.5	925	740	116	47	41	2.95	ND	44.61	465	22	1.5
29	B29	Ishwerpura	HP	7.1	1415	897	123	60	61	3.12	ND	91.15	507	43	8.8
30	B30	Ishwerpura	HP	8.1	964	725	73	39	45	4.26	ND	5.83	547	9	1.5
31	B31	Baligaon	HP	7.5	522	463	63	23	27	3.55	0.48	12.68	315	11	7.0
32	B32	Naika Tola	HP	7.7	405	360	41	30	10	0.48	0.24	6.76	243	8	20.4
33	B33	Jaithwar	HP	7.5	850	594	95	21	32	1.18	ND	61.03	350	19	15.1
34	B34	Bahnuwa	HP	7.4	629	497	66	18	24	0.87	0.26	23.47	334	14	16.8
35	B35	Andhari	HP	8.3	277	237	32	10	13	2.01	0.24	6.07	166	8	0.0
36	B36	Andhari	HP	8.0	482	379	54	24	21	0.75	0.45	4.48	263	8	2.3
37	B37	Sahar	HP	8.2	815	623	73	31	30	0.42	0.39	41.45	411	13	22.2
38	B38	Bhagwanpur	HP	8.1	942	403	50	33	17	0.45	0.48	11.06	278	11	1.1
39	B39	Bibiganj	HP	7.9	592	402	64	19	21	2.31	ND	8.38	275	11	ND
40	B40	Maulighat	HP	8.2	526	381	38	19	52	5.73	ND	41.48	200	25	ND
41	B41	Maulighat	HP	7.6	1033	828	74	52	35	4.12	ND	9.52	639	11	0.7
42	B42	Mauzampur	HP	7.7	815	709	135	39	38	2.39	ND	24.21	456	11	2.2
43	B43	Bindgaon	HP	8.2	380	267	41	14	14	2.03	0.32	6.05	166	9	ND
44	B44	Bindgaon	HP	7.7	732	593	73	28	13	3.13	ND	12.44	455	8	0.2
45	B45	Manikpur	HP	7.9	584	495	85	20	13	2.11	ND	5.58	363	5	0.1

HP= Hand Pump, GR= Ganga River, SR= Son River



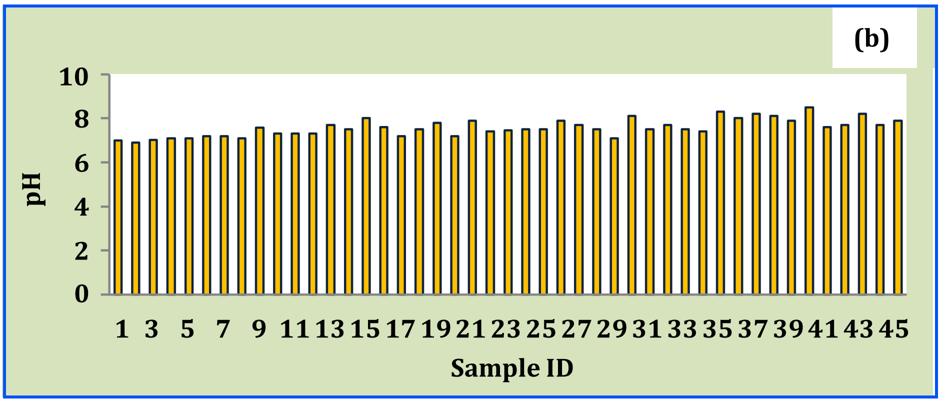
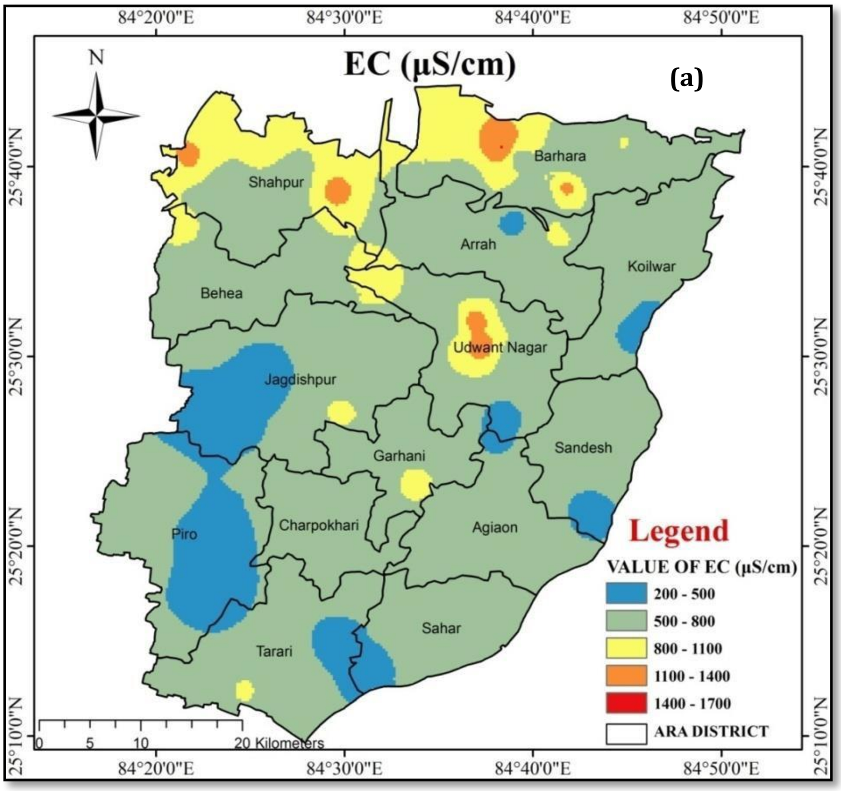


Figure 5.1: (a) Spatial variation of pH during post monsoon (b) Bar chart diagram of pH in pre monsoon



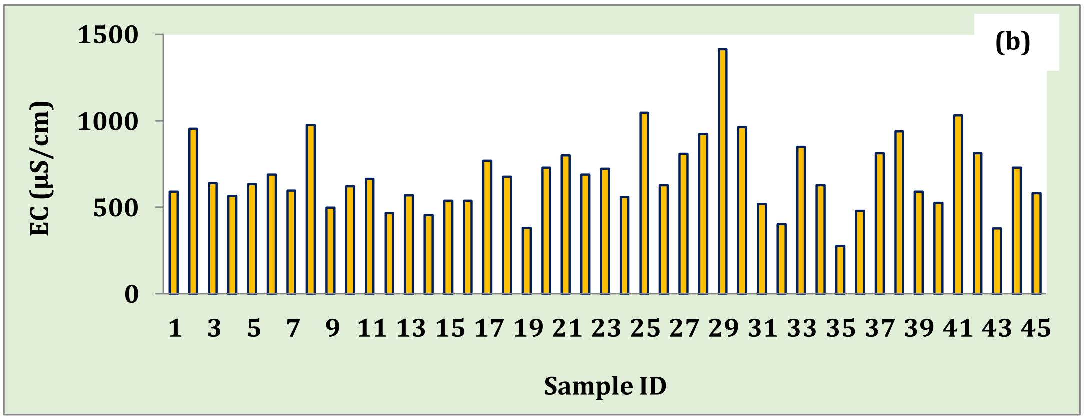


Figure 5.2: (a) Spatial variation of EC during post monsoon (b) Bar chart diagram of EC in pre monsoon

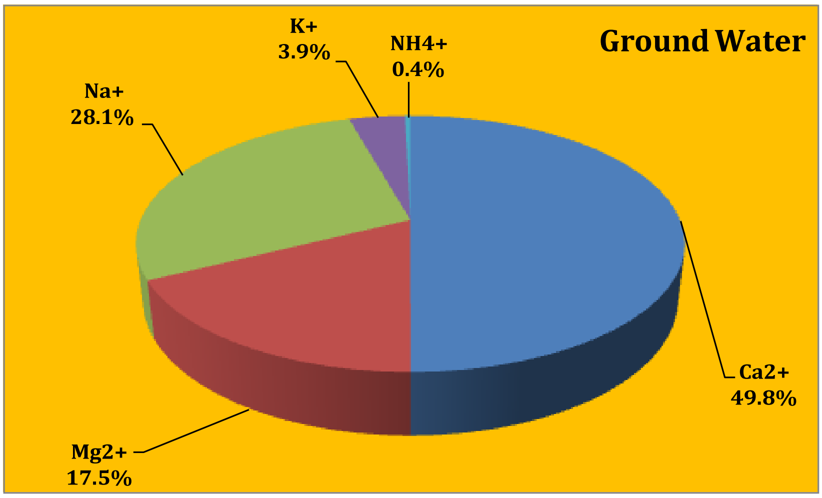
Total Dissolved Solid (TDS): TDS of water includes all dissolved material in solution, whether ionized or not. TDS is numerical sum of all mineral constituents dissolved in water and is expressed in mg/L. BIS (2012) have prescribed 500 mg/L as the acceptable limit and 2000 mg/L as permissible limit in absence of alternate source for drinking and other domestic usage. The TDS concentration of water samples collected during post monsoon are ranged from 271 to 1126 mg/L (mean: 496 mg/L) for groundwater, 300 to 560 mg/L (mean: 337 mg/L) for Ganga river and 174 to 212 mg/L (mean: 195 mg/L) for Son river whereas in pre-monsoon season, TDS ranged from 342 to 1034 mg/L with an average value of 557 mg/L for GW samples. The results show that about 38 % & 48 % of the groundwater samples exceeded acceptable limit (500 mg/L) and none of the sample was exceeding the permissible limit of BIS (2012) during post-monsoon and pre-monsoon seasons respectively.

5.1.2 Major ions chemistry

5.1.2.1 Major cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+})

The major cations include Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}. The water chemistry of the area is dominated by alkaline metals. In general water sampling results showing elemental abundancefollows the order $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$ for all sources i.e. groundwater, Ganga and Son rivers (Fig. 5.3) during both the seasons.

Calcium (Ca^{2+}): Calcium ions and calcium salt are the most commonly encountered substances in water. Calcium in water arises mostly from the dissolution of Ca bearing minerals of the aquifer formation and often it is the most abundant cation in water. Weathering and dissolution of calcium carbonate (limestone and dolomite) and calc-silicate minerals (amphiboles, pyroxenes, olivine, biotite etc.) are the most common source of calciumin aquatic system. In the present study, calcium alone constituting 50.6% in groundwater, 50.8% in Ganga water, and 58.9% in Son water of the total cations (TZ^{+}). Table 5.1 shows thecalcium concentration range for different sources i.e. 32.0 to 101 mg/L for groundwater, 33.3to 51.7 mg/L for Ganga river and 22.9 to 30.8 mg/L for Son river during post monsoon season while in pre monsoon calcium varies from 31.9 mg/L to 140 mg/L with an average concentration value of 74 mg/L in groundwater samples. The high concentration of Ca^{2+} are in agreement with the value reported by Bhattacharya et al. (1997).



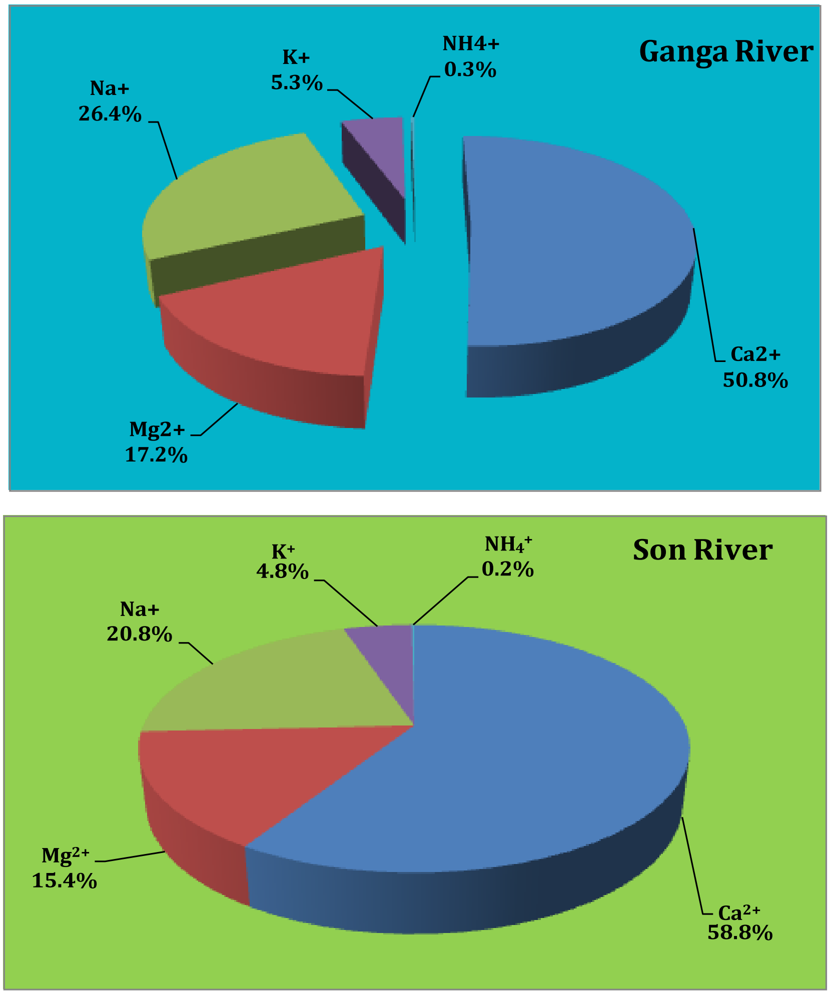


Figure 5.3: Contribution of cations towards the total cationic charge (TZ^+)

Abundance of calcium may be because of weathering of carbonate mainly gypsum, plagioclase and feldspar minerals, which are abundant in the floodplain regions. BIS (2012) have prescribed 75 mg/L as acceptable limit and 200 mg/L as permissible limit for calcium in absence of alternate source for drinking and other domestic usage. Spatial distribution map and bar chart of Ca in groundwater samples for post monsoon and pre monsoon have been shown in Fig. 5.4. The results show 20% & 42% of samples are exceeding the acceptable limit (75 mg/L) but all the samples fall within permissible limit as prescribed by BIS, 2012.

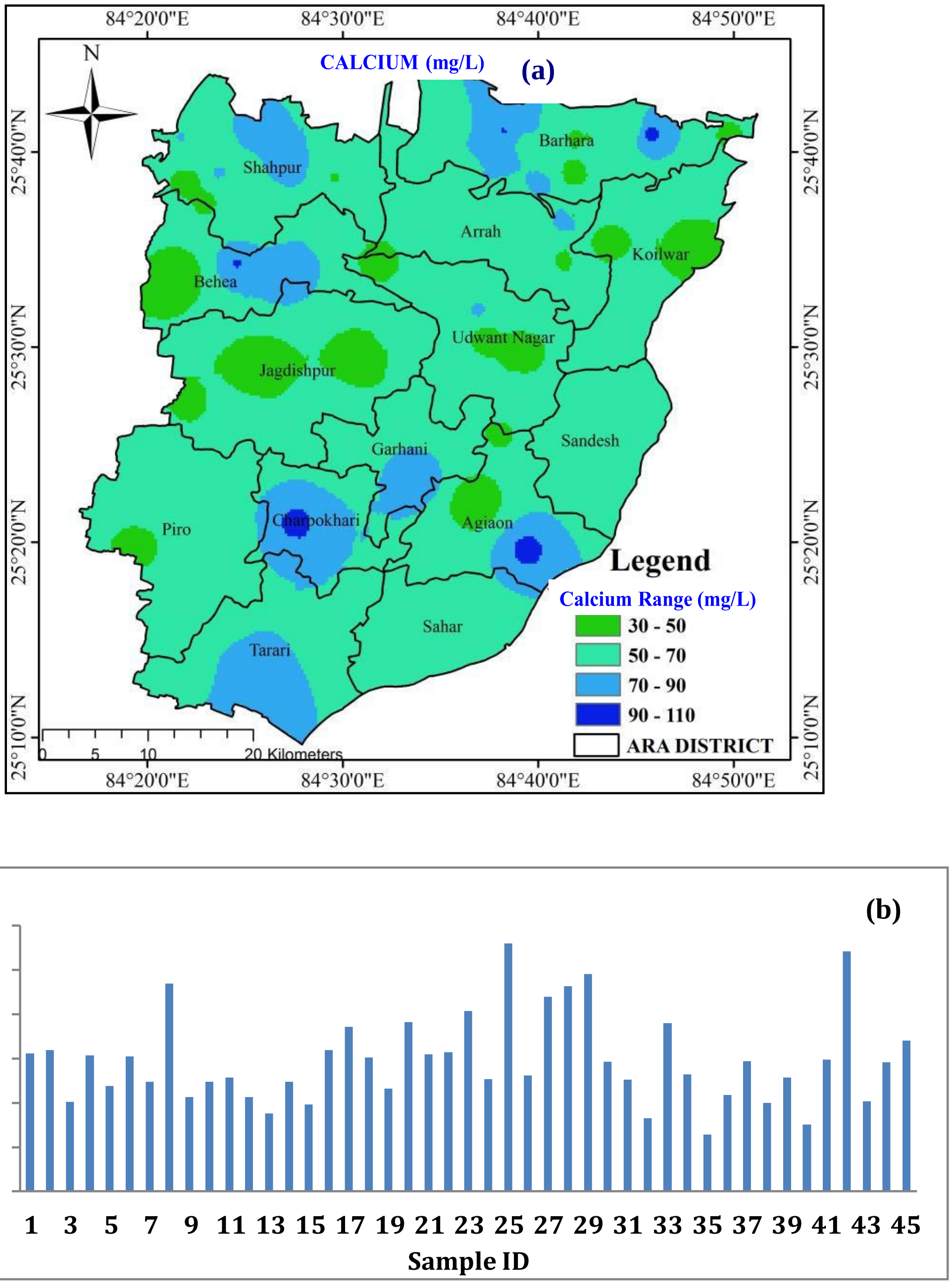
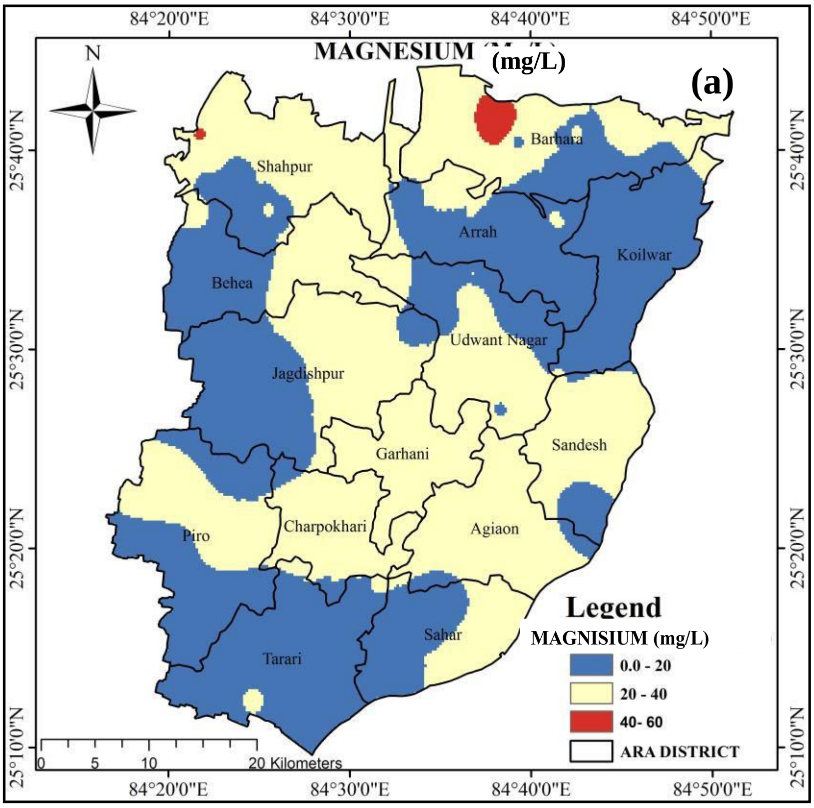


Figure 5.4: (a) Spatial variation of Ca in post monsoon (b) Bar chart diagram of Ca in pre monsoon seasons

Magnesium (Mg^{2+}): Mg^{2+} is abundant in earth crust and it is a common constituent of natural water. Clay minerals, dolomite, pyroxenes are the common source minerals for magnesium in the water. The principle source of magnesium in natural water is ferromagnesian mineral in igneous rock and magnesium carbonate in sedimentary rock. The sulphate and chloride of magnesium are very soluble. In the present study, magnesium concentration varies from 8.1 to 71.6 mg/L in groundwater, 8.7 to 18.0 mg/L in Ganga river and 6.0 to 8.2 mg/L for Son river in post monsoon season while in pre monsoon, Mg varies from 12 mg/L to 65 mg/L with an average concentration value of 27.1 mg/L in groundwater (Fig. 5.5). The presence of calcium and magnesium make the water hard. BIS (2012) have prescribed 30 mg/L as acceptable limit and 100 mg/L as permissible limit for magnesium in absence of alternate source for drinking and other domestic usage. Results suggest that 90.0 % & 77.7 % of groundwater samples are within acceptable limit for drinking water, but allthe samples are within the permissible limit during post monsoon and pre monsoon season.



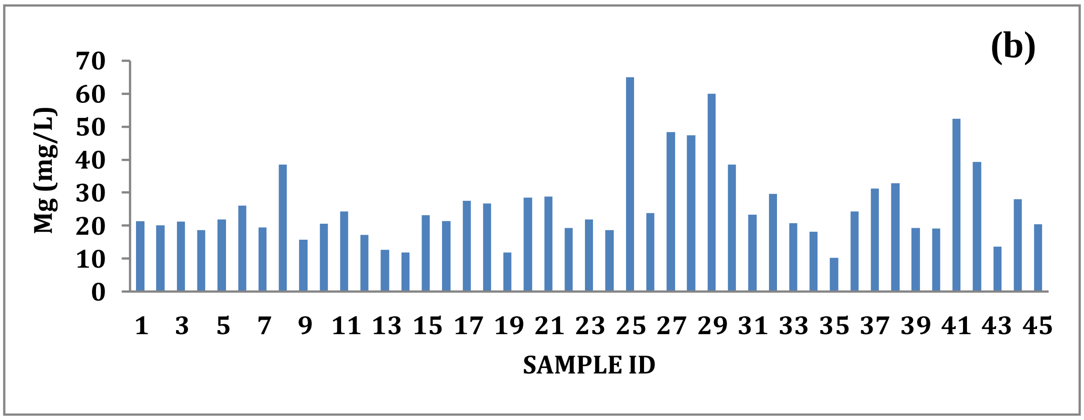
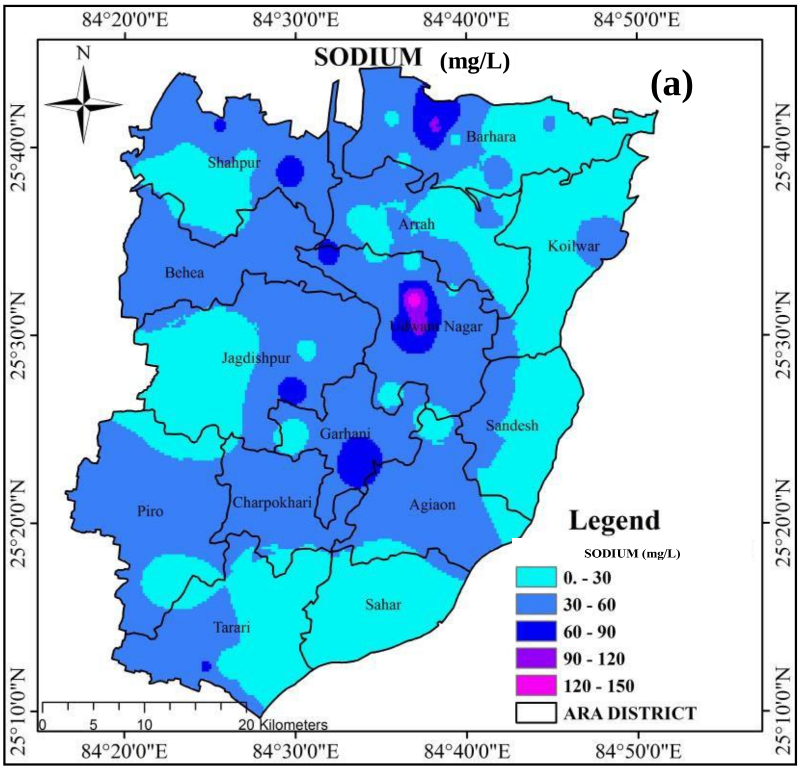


Figure 5.5: (a) Spatial variation of Mg during post monsoon (b) Bar chart diagram of Mg in pre monsoon

Sodium (Na^+): The sodium in the aquatic system is derived from the atmospheric deposition, evaporate dissolution and silicate weathering. The evaporate encrustations of sodium/potassium salts may also be developed due to cyclic wetting and drying periods causes the formation of alkaline/saline soils, which may also serve as a source of sodium and potassium. The weathering of Na and K silicate minerals like albite, anorthite, orthoclase and microcline are the major source of the Na and K in the aquatic system. Sodium concentration ranges between 0.3 - 137.1 mg/L for groundwater, 13.8 to 31.0 mg/L for Ganga river and 8.6 to 10.7 mg/l for Son river water samples during post monsoon while in pre monsoon, sodium concentration ranges from 10.0 mg/L to a maximum of 72.7 mg/L with an average concentration value of 27.4 mg/L in groundwater (Fig. 5.6). No health-based guideline value has been derived, as the contribution from drinking water to daily intake is small (WHO, 2011). Based on taste threshold, the recommended concentration of sodium in the water should be less than 200 mg/L and results suggest that all of the total analysed samples are wellwithin this category.



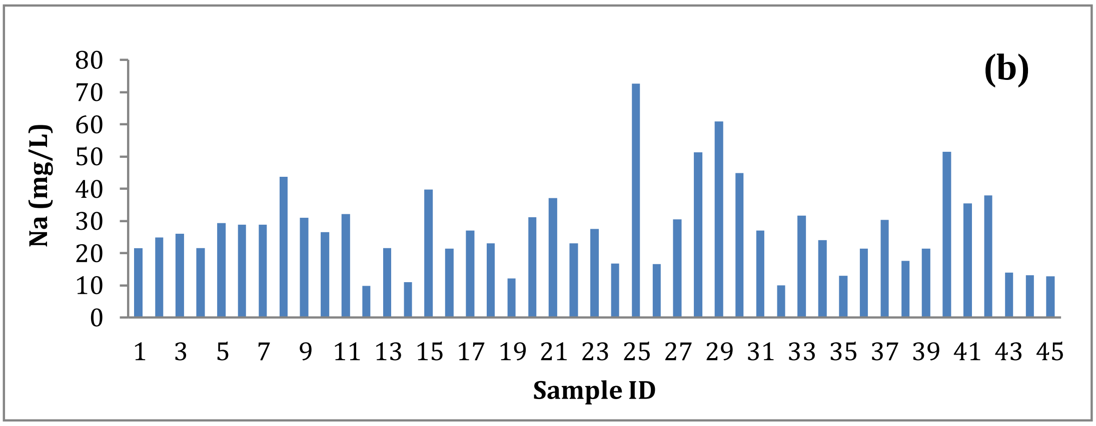


Figure 5.6: (a) Spatial variation of Na during post monsoon (b) Bar chart diagram of Na in pre-monsoon

Potassium (K^+): Potassium is nearly as abundant as sodium in igneous rocks and metamorphic rocks, its concentration in groundwater is one-tenth or even one-hundredth that of sodium. Parity in concentration of sodium and potassium is found only in waters with low mineral contents. Two factors are responsible for the scarcity of potassium in groundwater, one being the resistance of potassium minerals to decomposition by weathering and other is the fixation of potassium in clay minerals formed due to weathering. In the present study, potassium is the least abundant cation and constitutes 3.9%, 5.3% and 4.8% of the total cationic charge in ground water, Ganga and Son rivers samples respectively. In post monsoon,Potassium concentration varies between ND-32.5 mg/L for groundwater, 3.5 to 5.2 mg/L for Ganga river and 2.1 to 2.5 mg/L for Son river while in pre-monsoon, potassium concentration in groundwater samples ranges between 0.4 mg/L and 45 mg/L with an average value of 4.3 mg/L (Fig. 5.7).

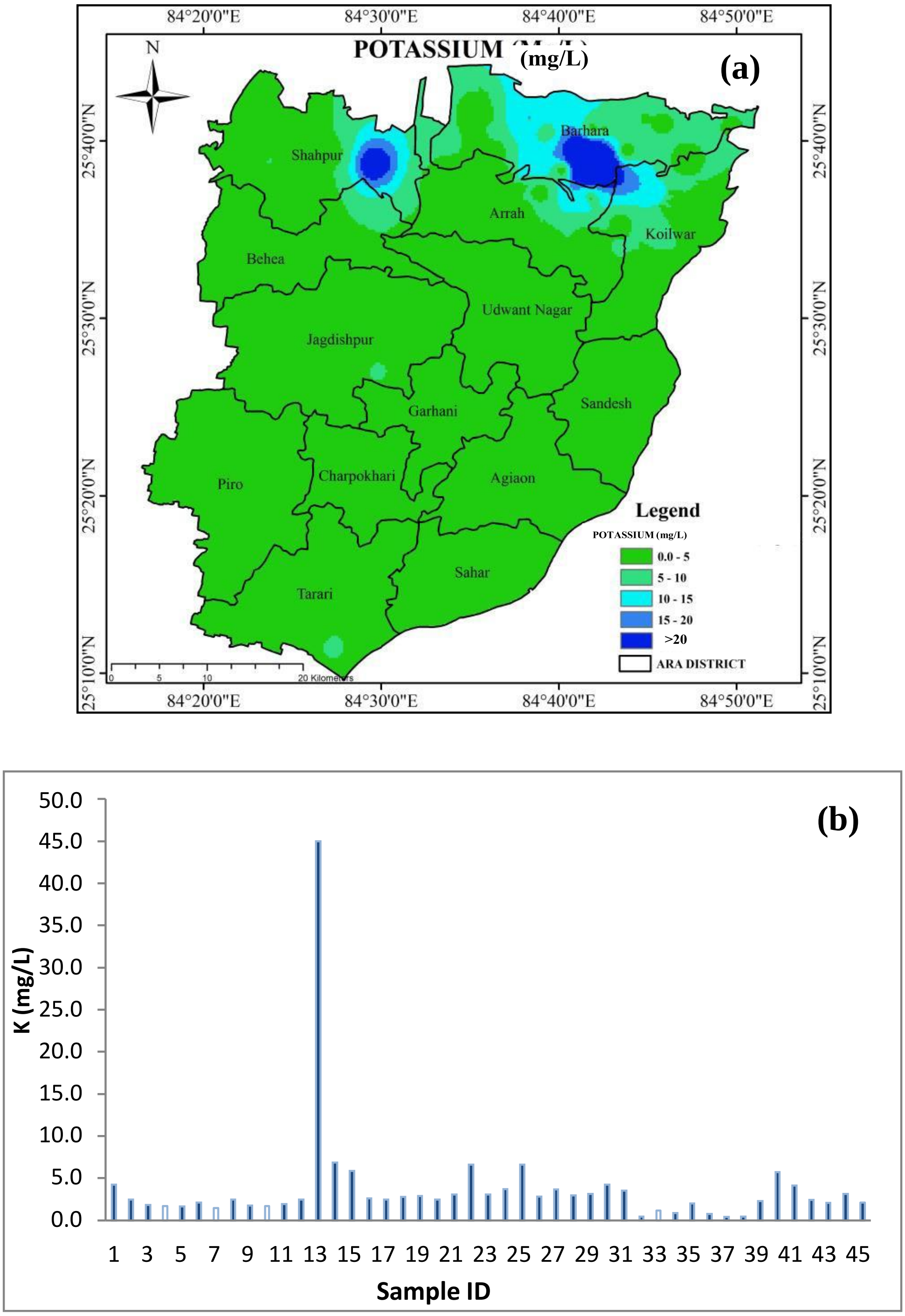
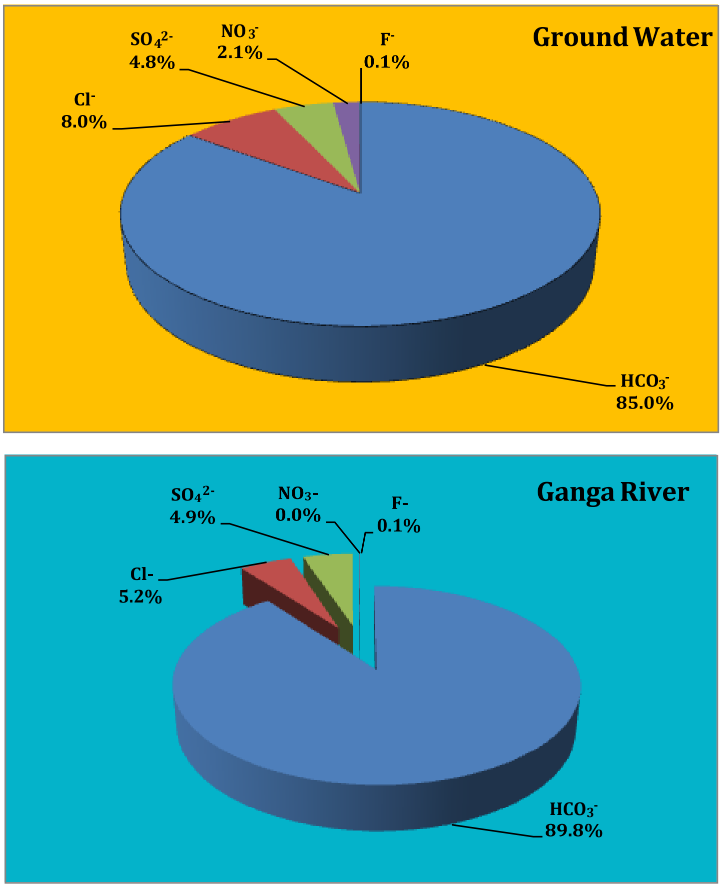


Figure 5.7: (a) Spatial variation of K during post monsoon (b) Bar chart diagram of K in pre monsoon

5.1.2.2 Major anions (HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, and F^-)

The anion chemistry of the analysed samples show the abundance in the order of $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > F^-$ in majority of the groundwater and river water samples. The plot (Fig. 5.8) of analysed data on anion diagram showing the relative % of the different anions towards the total anionic charge balance (TZ^-).

Bicarbonate (HCO_3^-): The bicarbonates & carbonate are derived mainly from the soilzone CO_2 and at the time of weathering of parent minerals. The soil zone in subsurface environment contains elevated CO_2 pressure (produce as result of decay of organic matter and root respiration), which in turn combines with rainwater to form bicarbonate. Bicarbonate may also be derived from the dissolution of carbonates and-or silicate mineralsby the carbonic acid. Bicarbonates contribute to alkalinity (acid neutralizing capacity), and BIS (2012) has prescribed 200 mg/L as acceptable limit and 600 mg/L as permissible limit inabsence of alternate source for drinking and other domestic usage.



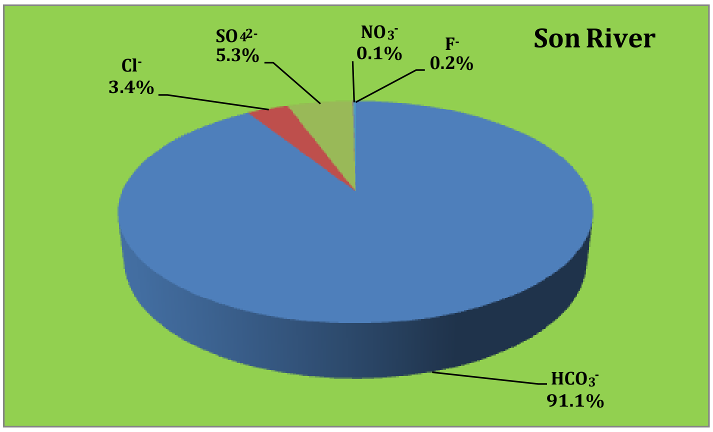
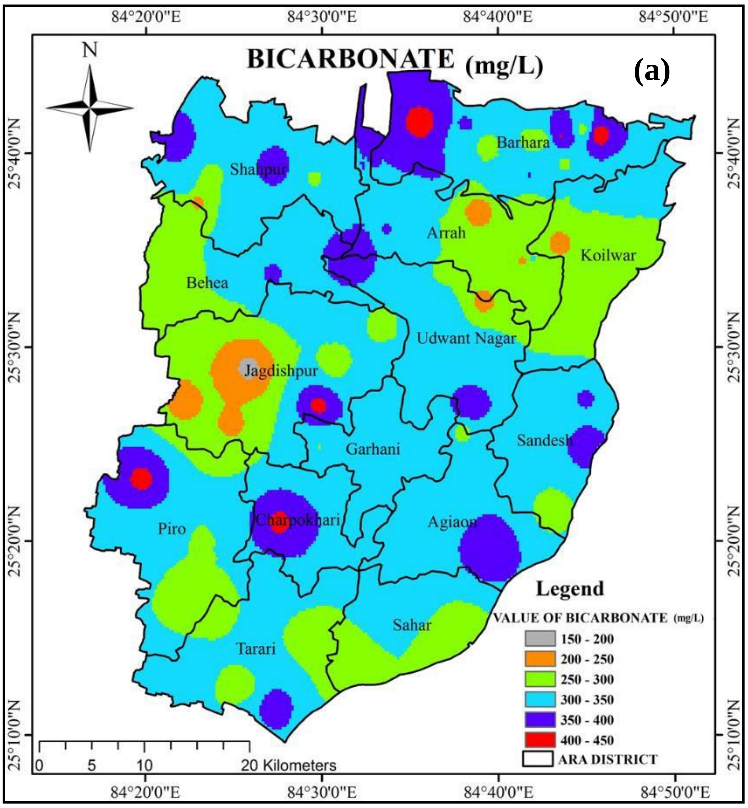


Figure 5.8: Contribution of anions towards the total anionic charge (TZ^-).

HCO_3^- is most abundant elements and alone constitute 84.8% in groundwater, 89.9% in Ganga water and water 91.1% in Son river of the total anions (TZ^-). The HCO_3^- concentration ranges from 186 to 443 mg/L for groundwater, 174 to 284 mg/L for Ganga river and 121 to 150 mg/L for Son river during post monsoon, while in pre monsoon, HCO_3^-concentration varies from 240 mg/L to 639 mg/L with average concentration 389 mg/L in groundwater (Fig. 5.9). High concentration of bi-carbonate found in the analysed samples indicates weathering of carbonates minerals.



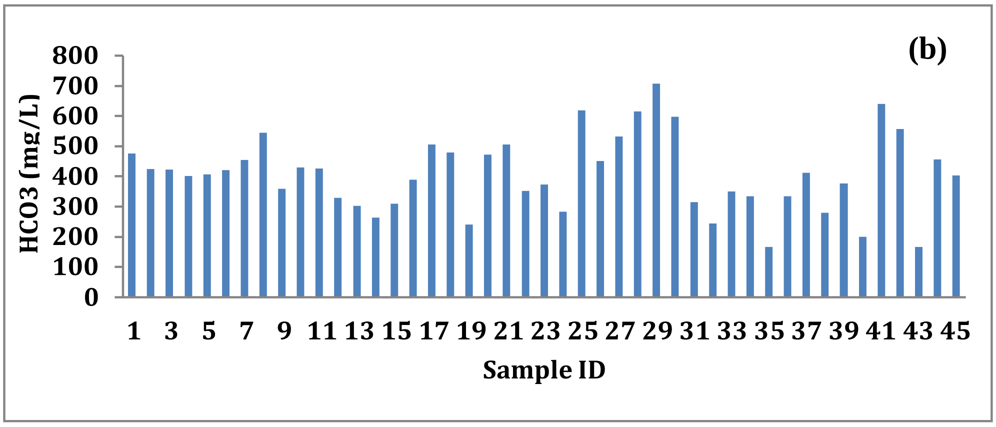


Figure 5.9: (a) Spatial variation of HCO_3^- during post monsoon (b) Bar chart diagram of HCO_3^- in pre monsoon

Chloride (Cl^-): The chloride concentration varies from 0.68 to 183 mg/L (mean 29.6 mg/L) for groundwater, 6.5 to 21.9 (mean 13.5 mg/L) for Ganga river and 4.1 to 5.9 mg/L (mean 5.0 mg/L) for Son river water samples of post monsoon season whereas in pre monsoon, it varies between 1.22 mg/L to 91.15 mg/L in groundwater samples (Fig. 5.10) with average concentration of 17.5 mg/L. BIS (2012) has prescribed chloride concentration 250 mg/L as acceptable limit and 1000 mg/L as permissible limit in absence of alternate source for drinking and other domestic usage. Chloride concentrations in all the analysed samples were within the acceptable limit prescribed by BIS during both the seasons. No health- based guideline value is proposed for chloride in drinking water. Chloride is present in lower concentrations in common rock types than any of the other major constituents of natural water and it is assumed that bulk of the chloride in ground water is primarily either from atmospheric source, sea water contamination or from anthropogenic sources. Abnormal concentration of chloride may result from pollution by sewage wastes.

Fluoride (F^-): Fluoride concentration ranges between ND - 1.2 mg/L for groundwater, 0.1 to 0.3 mg/L for Ganga river and 0.2 to 0.3 mg/L for Son river water samples in post monsoon whereas in pre monsoon, concentration of fluoride in groundwater samples of study area varies between ND to 0.6 mg/L (average concentration 0.3 mg/L). Fluoride is found in all natural waters at some concentration. Seawater typically contains about 1 mg/L while rivers and lakes generally exhibit concentrations of less than 0.5 mg/L. In groundwater, however, low or high concentrations of fluoride can occur, depending on the nature of the rocks and the occurrence of fluoride-bearing minerals. Fluoride intake to humans is necessary as long as it does not exceed the limits.

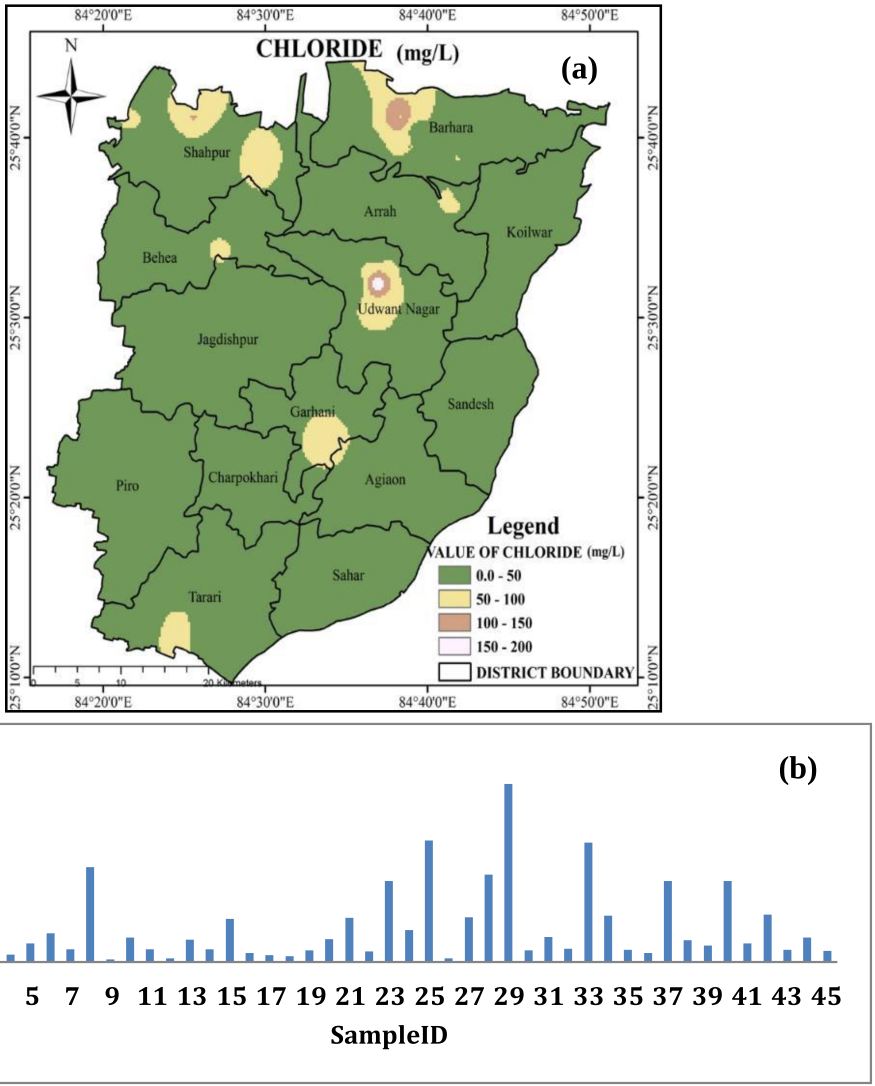
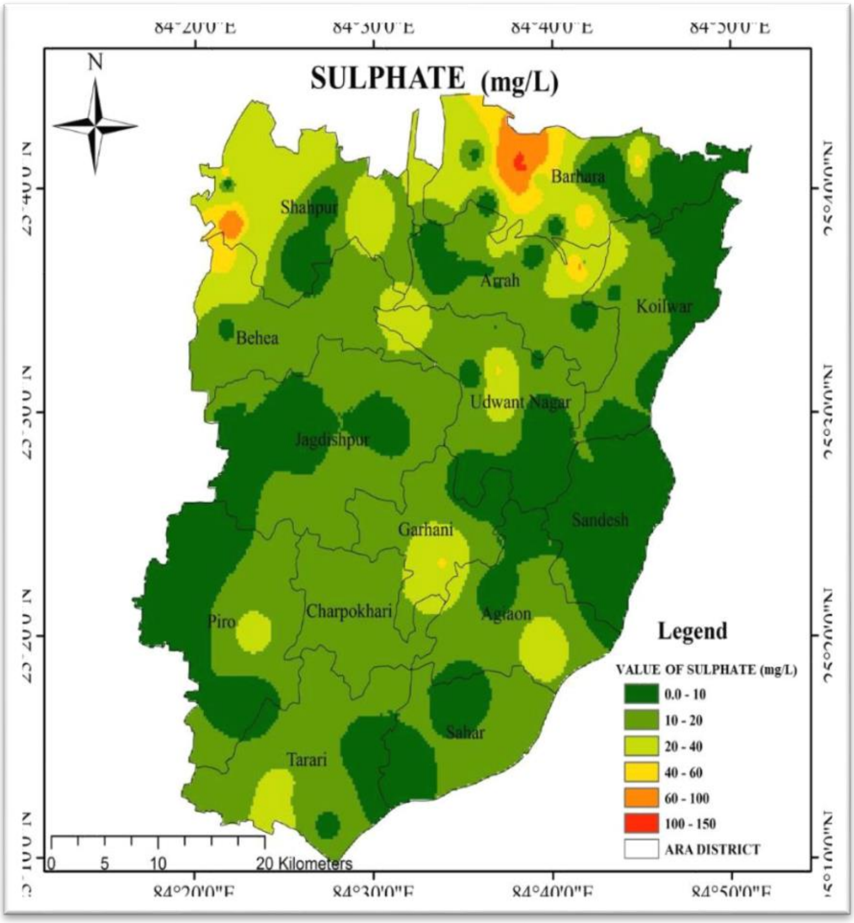


Figure 5.10: (a) Spatial variation of Cl during post monsoon (b) Bar chart diagram of Cl in pre monsoon

The WHO (2011) and BIS (2012) estimates the maximum allowable limit for fluoride uptake to human's in drinking water as 1.5 mg/L. Excess fluoride intake causes different types of fluorosis, primarily dental and skeletal fluorosis. The fluoride concentration in all the samples were found well within acceptable limit (1.0 mg/L) except one groundwater sample collected from Damodarpur village (1.2 mg/L) which is less than prescribed permissible limit (1.5 mg/L).

Sulphate (SO_4^{2-}): High Sulphate concentration in drinking water can cause noticeable taste and very high levels might cause a laxative effect in unaccustomed consumers. Taste impairment varies with the nature of the associated cation; taste thresholds have been found to range from 250 mg/L for sodium sulphate to 1000 mg/L for calcium sulphate. High sulphate levels in drinking water may results in gastro-intestinal disorders. BIS (2012) has prescribed 200 mg/L as acceptable limit and 400 mg/L as permissible limit for sulfate in absence of alternate source for drinking and other domestic usage. Sulphate concentration ranges between 0.1 to 154.0 (mean 18.9 mg/L) for groundwater samples, 6.4 to 20.8 mg/L (mean 12.5 mg/L) for Ganga river and 7.2 to 8.5 mg/L (mean 7.9 mg/L) for Son river water respectively for post monsoon season, whereas sulphate concentration in pre monsoon (May 2019) varies between 3.8 mg/L to 43.3 mg/L (avg 11.3 mg/L) in groundwater samples (Fig. 5.11). Concentrations of sulphate in all the samples are found well within acceptablelimit (200 mg/L) during both the seasons.



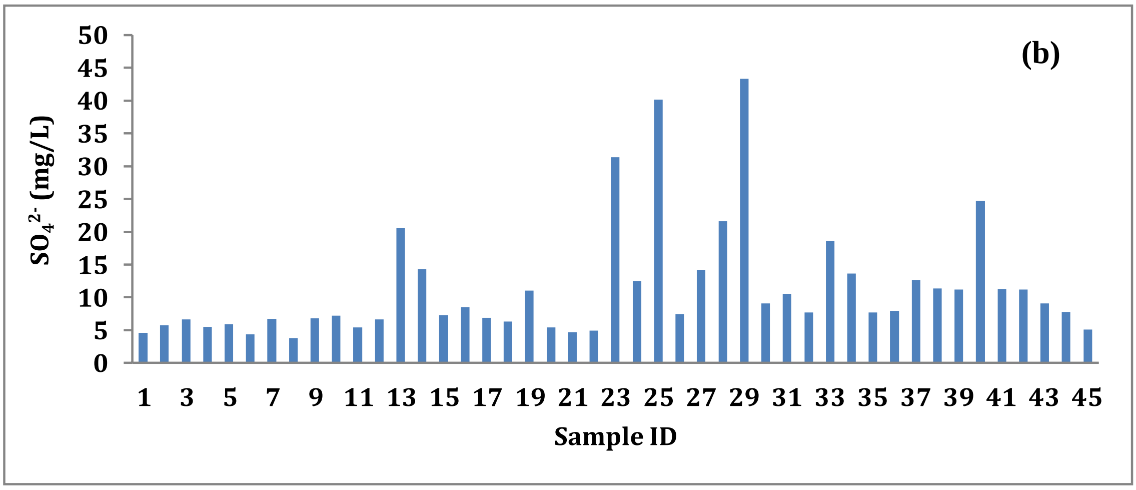


Figure 5.11: (a) Spatial variation of SO_4^{2-} during post monsoon (b) Bar chart diagram of SO_4^{2-} in pre monsoon

Nitrate (NO_3^-): NO_3^- is found naturally in the environment and is highly soluble in water. It is present at varying concentrations in all plants and is a part of the nitrogen cycle. Nitrate can reach both surface water and groundwater as a consequence of agricultural activity (including excess application of inorganic nitrogenous fertilizers and manures), from wastewater disposal and from oxidation of nitrogenous waste products in human and animal excreta, including septic tanks. Figure 5.12 showing nitrate concentration ranges between ND – 70.2 mg/L (mean: 7.9 mg/L) for groundwater, ND to 0.5 mg/L (mean 0.1 mg/L) for Ganga and Son rivers water samples in post monsoon season. However, concentration of nitrate in analysed ground water samples ranges from ND to 29.4 mg/L withthe average concentration value of 6.7 mg/L during pre-monsoon season. The BIS, 2012 prescribed the acceptable limit for the drinking water is 45 mg/L and no relaxation in permissible limit in absences of alternate sources. If nitrite concentration is more than prescribed limit then it may cause Blue Baby Syndrome disease. In the study area mostly samples having lower nitrate concentration then BIS prescribedlimit except one location (village Badka Luhar).

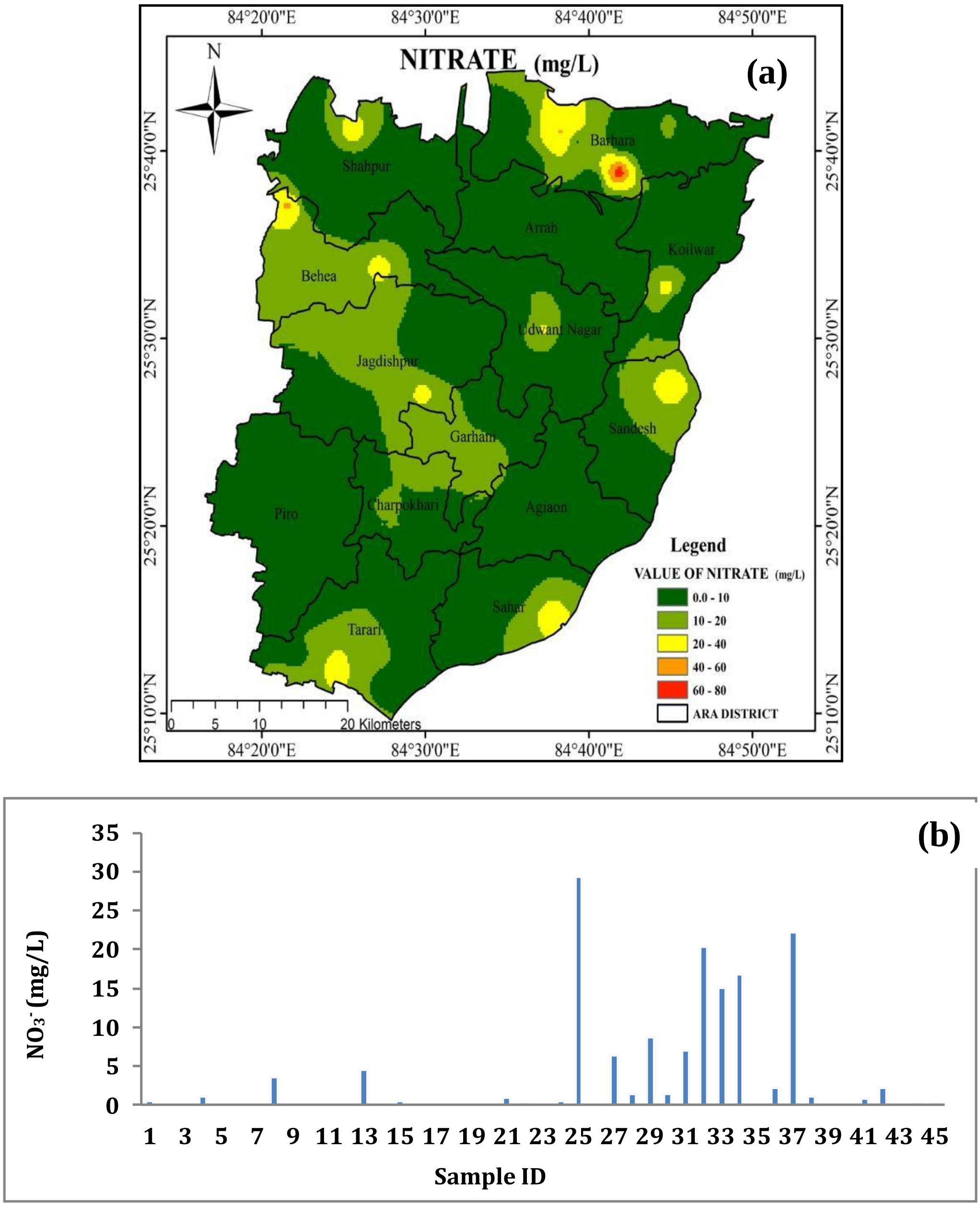


Figure 5.12: (a) Spatial variation of NO_3^- during post monsoon, (b) Bar chart diagram of NO_3^-in pre monsoon

5.1.3 Classification of Water

Hydro-geochemical evolution of ground water depends on water–aquifer matrix interaction, ground water residence time within the aquifer and the associated chemical process during recharge e.g. cation exchange (Drever, 1997). The ground water from older and younger alluvium plain in the study area shows a distinct relationship with major solutes in the groundwater. Piper trilinear diagram is generally used for classifying groundwater. In piper trilinear diagram, cations, expressed as percentages of total cations in mill equivalents per liter plot asa single point on the left triangle, while anions similarly expressed as percentages of total anions appear as a point in the right triangle. These two points are then projected into the central diamond-shaped area parallel to upper edges of the central area. This single point is thus uniquely related to the total ionic distribution. The trilinear diagram conveniently reveals similarities and differences among groundwater samples because those with similar qualities will tend to plot together as groups. The ionic signature helps in knowing the principal ions controlling the water chemistry. Using the classification scheme as shown in Fig. 5.13; Piper diagram shows hydro-geochemical facies of Ca-Mg-HCO_3 type for groundwater in the study area. The published articles by the researchers (Zheng et al., 2004 and Mukherjee and Fryar, 2008; Mukherjee et al., 2012) have mentioned that high HCO_3^- concentration play important roles in hydro-chemical evolution and trace metal mobilization in the Middle Gangetic plain. In the present study we have also observed high HCO_3^- in and around the younger alluvial aquifers. A recent work by Wu et al., 2020 indicates that less than 15 mg/L HCO_3^- at pH 7 decreases arsenic mobility, therefore, rainwater harvesting can be a mitigative strategy to contain the As in the sediments. Gibbs plots indicates the dominance of rock-water interactionfollowed by evaporation enrichment which is mainly irrigation return flow driven (Fig 5.13 b).

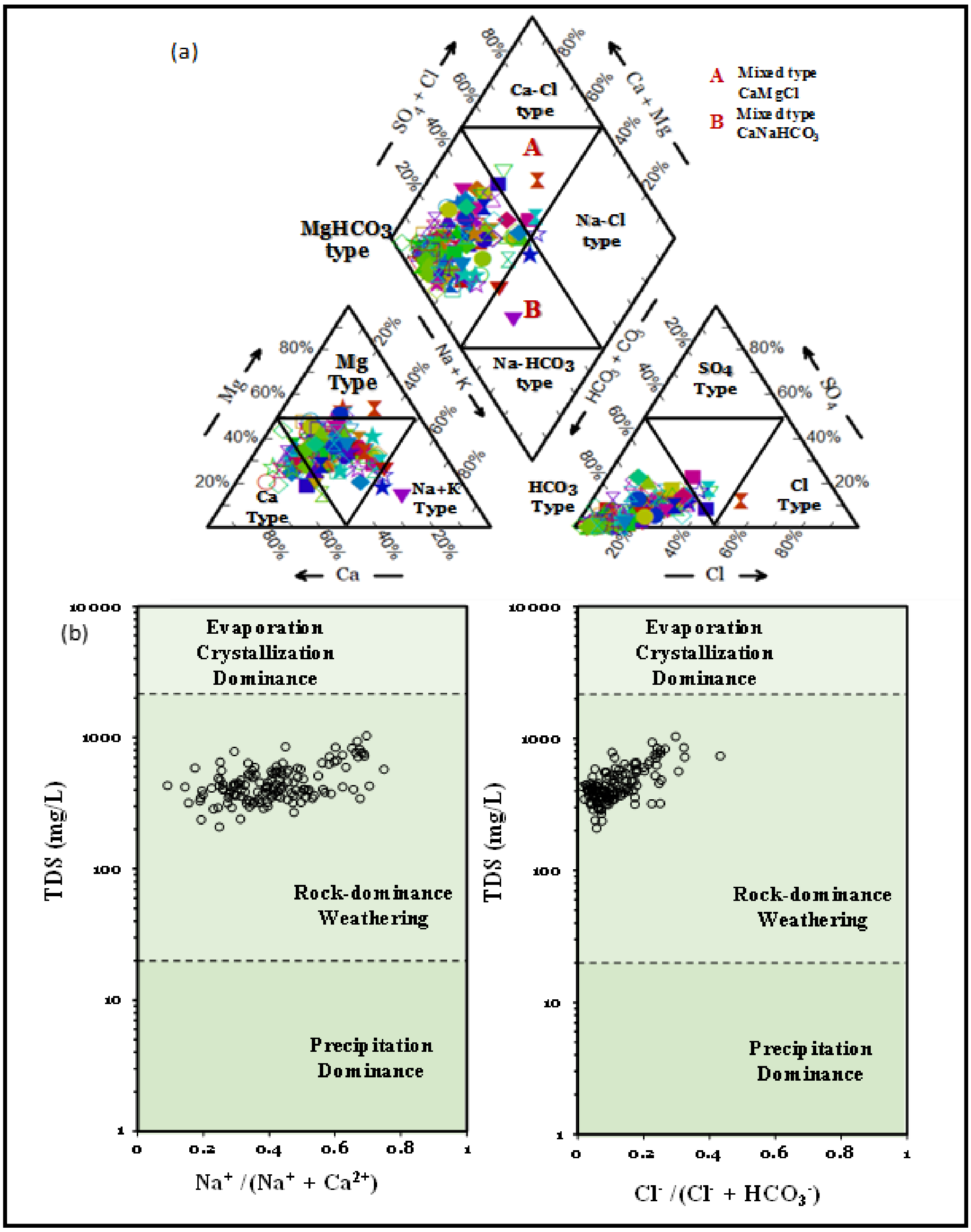


Figure 5.13: (a) Piper trilinear diagram illustrating hydro-geochemical regime in the study area **(b)** delineation of dominant hydro geochemical processes through Gibbs plot.

5.1.4 Hydro-geochemical processes

The chemical constituents of groundwater are influenced by many factors such as rainwater chemical properties, mineral composition of rock, groundwater residence time and anthropogenic activities involved in the area (Andre et al., 2005). The atmospheric sources may contribute to the dissolved salts present in the groundwater and it may be evaluated by calculating the ratios of elements to Cl^- (Zhang et al., 1995). In the present study, the average Na^+/Cl^- and K^+/Cl^- ratios for the groundwater (1.48 and 0.08) are high and this suggest that major ions in the groundwater are most likely to be occurred due to weathering of rock and limited contribution from atmospheric deposition. The Gibbs's diagram (Gibbs, 1970) specifies the dominance of rock water interaction which is controlling the geochemistry of the study area (Fig. 5.13 b). Further, a higher ratio of $HCO_3^-/(SO_4^{2-} + Cl^-)$ i.e. 2.7 also indicates rock weathering playing a major role in geochemical evolution of groundwater in comparisonwith atmospheric deposition and anthropogenic sources (Rose, 2002).

Several hydrogeochemical bivariate plots are drawn and presented in Figure 5.14. The plot between (Ca^{2+}+Mg^{2+}) and (HCO_3^-+SO_4^{2-}) demonstrate the dissolution of calcite, dolomite and gypsum in the groundwater system. In the present study, the plot displays that majority of the samples are below the equiline, however few data points lie on equiline (Fig. 5.14a). The data points below the equiline indicates the excess of HCO_3- and SO_4^{2-} over Ca^{2+} and Mg^{2+} which suggest contribution from non-carbonate source. In the carbonate weathering reaction, theCa^{2+} and Mg^{2+} (carbonate derived) should be equal to carbonate derived HCO3- as per the stoichiometry (Singh et al., 2013). The plot of (Ca^{2+}+Mg^{2+}) vs HCO_3^- indicate the dominance of carbonate or silicate weathering in the natural water system (Pant et al., 2021b). Few data are lying on equiline of (Ca^{2+} + Mg^{2+}) vs HCO_3^- plot (Fig. 5.14b) shows prevalence of both carbonate and silicate weathering. However, maximum number of samples are near Ca^{2+}+Mg^{2+} axes designating carbonate weathering. Few samples show a deficiency of Ca^{2+} and Mg^{2+} relative to HCO_3^- and it can be inferred that excess bicarbonate is balanced by the alkalies (Na^+ and K^+) and it may be present through silicate weathering. Source for $Ca^{2+}$and Mg^{2+} ions can be interpreted using the Ca^{2+} vs HCO_3^- and Ca^{2+} vs SO_4^{2-} plots. The plot of Ca^{2+} vs HCO_3^- (Fig. 5.14 c) suggest calcite and dolomite dissolution as data points are near HCO_3^- axis but if we see the plot Ca^{2+} vs SO_4^{2-} plot (Fig. 5.14 d), the concentration of Ca^{2+} is higher than SO_4^{2-} indicating insignificant amount of gypsum present in the study area.

The average (Ca^{2+} + Mg^{2+})/TZ^+ ratio is 0.72 reflecting the high abundance of calcium and magnesium ions and it justifies the weathering of carbonate minerals in the middle Ganga plain. The average (Na^+ +K^+)/TZ^+ ratio is 0.28 which indicates that silicate weathering is also occurring in the study area. It may be noticed from the plot of Calcium and Magnesium versustotal cations (Fig. 5.14e) that the data points lie below the 1:1 line which is quite obvious, and it is more prominent at higher concentration which reflects sodium and potassium concentration increased with increasing dissolved solids. The Na^+ and K^+ concentrations in the groundwater are notably excess over chloride and the ratio i.e. 2.67

suggesting that the silicate weathering rich in sodium and potassium may be the source of Na^{+} and K^{+} in groundwater. The ratio of (Ca^{2+} + Mg^{2+}) and (Na^{+} +K^{+}) is 2.61, and it can be advocated that the geochemistry of the groundwater is mainly controlled by carbonate weathering with less contribution from silicate weathering (Fig. 5.14(f)). Therefore, from the above geochemical data, it can be concluded that the dissolution/weathering of carbonate rock acts as a major contributor for Ca^{2+}, Mg^{2+}, and HCO_3^{-}, however, alumino-silicates minerals are the major contributor for Na, K, and SiO_2 in the Bhojpur district. Similar observations have been made by other researchers regarding the geochemistry in the middle Ganga plain (Saha et al., 2011).

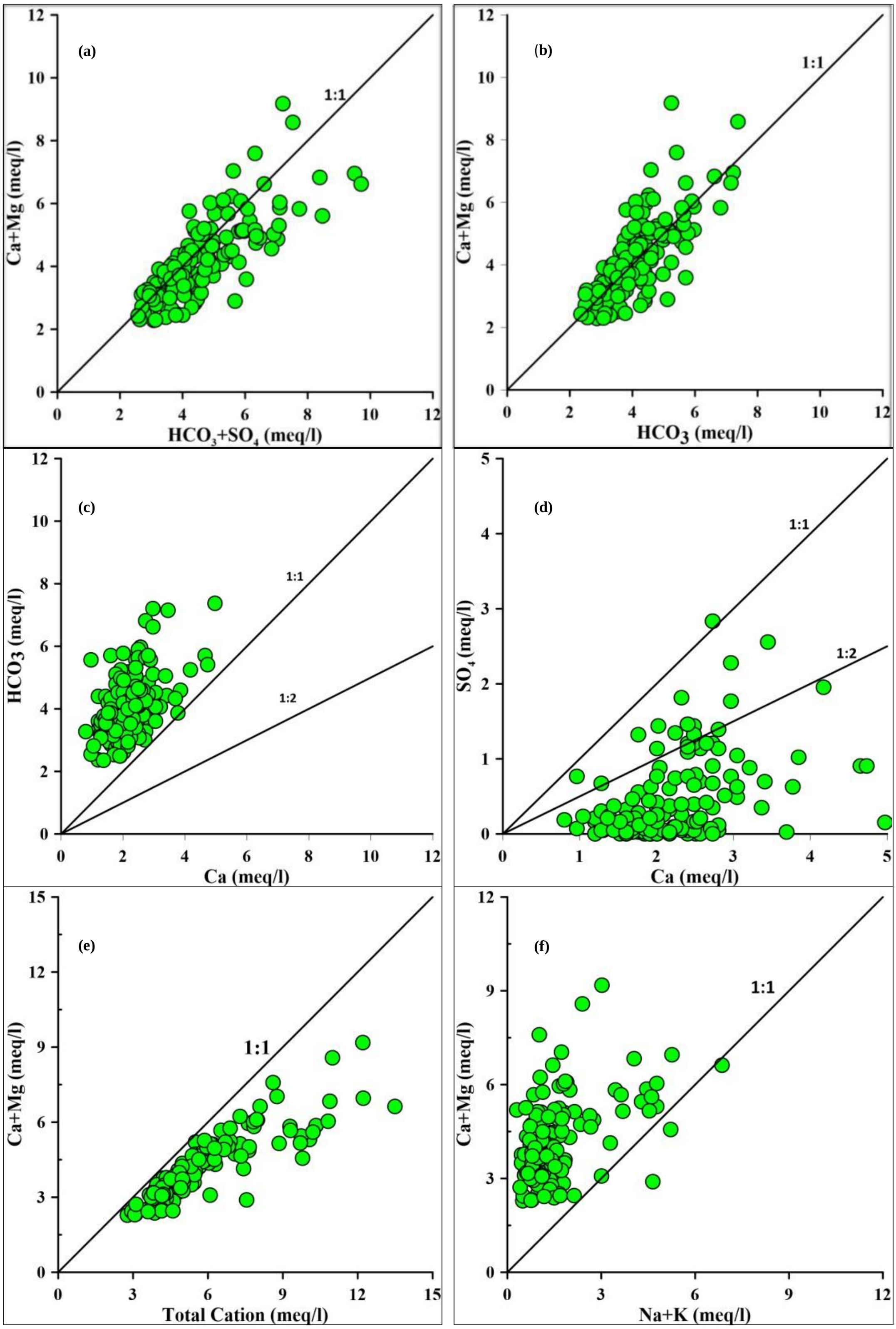


Figure 5.14: Scatter plots (a) Ca+Mg Vs HCO_3 + SO_4 (b) Ca+Mg Vs HCO_3 (c) Ca Vs HCO_3 (d) Ca Vs SO_4 (e) Ca + Mg Vs TZ^+ (f) Ca + Mg Vs Na +K

5.2 Fate and distribution of trace metals

Trace metals in ground water have a considerable significance due to their toxicity and adsorption behaviour. Trace or heavy metals are not biodegradable and enter the food chain through a number of pathways causing progressive toxicity due to the accumulation in human and animal organs during their life span on long term exposure to contaminated environments. The statistical results of trace metals (As, Cu, Cd, Ni, Al, Mn, Pb, Fe and Zn) are given in Table 5.4 and location-wise results are presented in the Table 5.5 and 5.6 for post monsoon & pre monsoon samples respectively. The toxic effects of these elements, extent and causes of their contamination in ground water is discussed in the following sections.

Table 5.4: Statistical evaluation of the trace metals concentrations in post monsoon of the study area (covering entire district)

PARAMETERS			Fe ppb	Mn ppb	Zn ppb	Al ppb	Cu ppb	Cd ppb	Ni ppb	As ppb	Pb ppb
BIS Limits		Acceptable	**300**	**100**	**5000**	**30**	**50**	**3**	**20**	**10**	**10**
		Permissible	**NR**	**300**	**15000**	**200**	**1500**	**NR**	**NR**	**50**	**NR**
Water Sources	Ground Water	Min.	ND	ND	ND	5.7	ND	ND	ND	ND	ND
		Max.	15000	6200	5300	235.7	19.5	0.9	5.0	206	19.7
		Avg.	1500	368	710	31.7	0.9	0.1	0.4	14.6	2.2
		S.D.	2750	730	1046	36.1	2.8	0.2	2.8	33.3	3.6
	Ganga River	Min.	120	69.6	227	149	0.4	ND	ND	2.4	ND
		Max.	310	141.6	749	185	3.2	0.9	ND	4.8	2.6
		Avg.	223	111	538	169	2.1	0.3	-	3.3	1.2
		S.D.	96	37.2	275	18.5	1.5	0.5	-	1.3	1.3
	Son River	Min.	220	14	6	210	ND	ND	ND	ND	ND
		Max.	660	153	211	352	3.1	0.2	4.4	2.0	2.5
		Avg.	402	50	74	279	1.1	0.1	0.9	0.4	0.6
		S.D.	163	58	83	66	1.3	0.1	2.0	0.9	1.1
	Ground Water	**Pre-monsoon season GW Samples' results**									
		Min.	60	2.1	110.4	35.1	ND	ND	ND	ND	ND
		Max.	14390	1303	2190.2	331.7	10.3	2.7	10.6	336.6	13.4
		Avg.	2933	411.5	321.6	73.6	3.5	0.7	1.2	77.9	6.4
		S.D.	3798	296.4	446.4	62.9	1.8	0.59	2.1	101.7	3.98

ND-Not detected, NR-No Relaxation

Table 5.5: Trace metal concentration in water samples of the study area during post monsoon

S.No.	Sample Code	Location	Block	Source	As ppb	Cd ppb	Cu ppb	Ni ppb	Pb ppb	Mn ppb	Al ppb	Fe ppb	Zn ppb
1	ARA_1	Dhanupura	Ara	HP	9.1	ND	3.1	ND	2.6	58	28	190	218
2	ARA_2	Moula Bagh	Ara	HP	1.7	0.2	0.6	ND	6.4	35	29	460	313
3	ARA_3	Bibiganj	Ara	HP	49.1	ND	ND	ND	6.2	329	31	1380	391
4	ARA_4	Gajrajpur	Udwantnagar	HP	9.5	0.1	ND	ND	0.1	856	207	1710	112
5	ARA_5	Goda devi	Ara	HP	53.7	0.1	ND	ND	1.8	208	23	3610	469
6	ARA_6	Bampali	Udwantnagar	HP	5.0	ND	ND	ND	ND	640	24	570	661
7	ARA_7	Dhobi ghat	Udwantnagar	HP	ND	ND	3.5	ND	1.7	37	27	1620	657
8	ARA_8	Dhanpura	Ara	HP	ND	ND	ND	ND	1.4	83	22	210	508
9	ARA_9	Mathulia	Ara	HP	29.1	0.3	6.9	ND	9.3	611	25	2930	1530
10	ARA_10	Mathulia	Ara	HP	25.3	ND	0.6	ND	ND	1050	40	3860	143
11	ARA_11	Barka lauhar	Barhara	HP	5.0	ND	ND	ND	1.8	954	24	330	1431
12	ARA_12	Bakhorapur	Ara	HP	ND	0.1	0.1	ND	4.7	438	19	320	1114
13	ARA_13	Barahara	Barhara	HP	16.8	ND	1.7	ND	7.4	144	19	1820	4236
14	ARA_14	Barahara	Barhara	GR	2.6	ND	2.8	ND	0.9	122	510	240	949
15	ARA_15	Ekona	Barhara	HP	2.2	ND	ND	ND	2.0	737	23	540	1515
16	ARA_16	Ekona*	Barhara	HP	16.0	0.2	1.4	ND	15.1	225	34	2770	1872
17	ARA_17	Sirsiyan	Barhara	HP	168.6	0.7	ND	ND	12.3	829	22	12040	2680
18	ARA_18	Paiga	Barhara	HP	28.3	ND	0.7	ND	7.3	465	37	2870	2002

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Location	Block	Source	As ppb	Cd ppb	Cu ppb	Ni ppb	Pb ppb	Mn ppb	Al ppb	Fe ppb	Zn ppb
19	ARA_19	Shivpur	Barhara	HP	ND	0.1	0.5	ND	6.9	433	21	610	1172
20	ARA_20	Englishpur	Barhara	HP	12.7	0.2	ND	ND	6.8	107	19	4200	1553
21	ARA_21	Jadopur	Ara	HP	11.7	0.2	ND	ND	4.9	296	17	2090	1089
22	ARA_22	Malther	Udwantnagar	HP	ND	ND	ND	ND	ND	114	23	230	254
23	ARA_23	Asani	Udwantnagar	HP	ND	ND	ND	ND	5.0	17	16	350	1229
24	ARA_24	Kaurva	Jagdishpur	HP	1.9	0.1	19.5	0.8	9.7	41	21	2570	1507
25	ARA_25	Khusma	Jagdishpur	HP	0.3	0.1	ND	ND	3.7	1194	16	6740	1473
26	ARA_26	Baligaon	Garhani	HP	7.8	ND	ND	ND	5.4	566	23	510	888
27	ARA_27	Tenduni	Jagdishpur	HP	ND	0.2	0.8	5.0	3.6	22	23	640	1588
28	ARA_28	Nayika Tolla	Jagdishpur	HP	16.5	ND	ND	ND	0.5	72	18	180	792
29	ARA_29	Keshari	Jagdishpur	HP	4.4	ND	ND	ND	4.0	24	15	770	1109
30	ARA_30	Chakk Tolla	Piro	HP	1.2	ND	0.5	1.9	0.2	66	21	530	96
31	ARA_31	Ojhawaliya	Piro	HP	ND	ND	ND	ND	ND	6201	11	50	105
32	ARA_32	AgionBazar	Piro	HP	ND	ND	ND	ND	ND	14	14	460	70
33	ARA_33	Nagri	Charpokhari	HP	0.5	ND	ND	ND	ND	13	19	430	103
34	ARA_34	Benuva Tolla	Garhani	HP	0.5	ND	ND	ND	ND	37	18	90	60
35	ARA_35	Ahdhrohara	Udwantnagar	HP	ND	ND	ND	ND	ND	4	17	150	67
36	ARA_36	Udwantnagar	Udwantnagar	HP	ND	ND	ND	ND	ND	115	17	240	72
37	ARA_37	Anhari	Sahar	SR	ND	ND	1.5	ND	ND	27	281	420	24

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Location	Block	Source	As ppb	Cd ppb	Cu ppb	Ni ppb	Pb ppb	Mn ppb	Al ppb	Fe ppb	Zn ppb
38	ARA_38	Anhari	Sahar	HP	ND	0.41	ND	ND	ND	18	18	750	83
39	ARA_39	Khutar	Tarari	HP	9.7	ND	ND	ND	ND	3	20	170	8
40	ARA_40	Bihta	Tarari	HP	ND	0.16	1.1	ND	3.0	21	21	430	1294
41	ARA_41	Bahnuwa	Tarari	HP	8.4	ND	ND	ND	1.6	12	25	190	16
42	ARA_42	Tarari	Tarari	HP	ND	ND	ND	ND	ND	6	34	580	23
43	ARA_43	Kharauha	Tarari	HP	ND	ND	ND	0.7	ND	8	20	130	23
44	ARA_44	Jethwah	Piro	HP	21.1	0.1	5.3	1.0	7.3	223	38	230	4997
45	ARA_45	Khayamnagar	Koilwar	HP	2.5	ND	ND	ND	ND	161	20	1930	73
46	ARA_46	Koilwar	Koilwar	HP	1.5	ND	ND	ND	ND	141	21	2600	53
47	ARA_47	Manikpur	Koilwar	HP	38.7	0.2	ND	0.4	ND	1232	19	6220	17
48	ARA_48	Manikpur	Barhara	SR	23.0	0.2	3.1	4.4	0.7	153	1042	320	89
49	ARA_49	Son River FP	Barhara	HP	88.5	0.4	ND	0.6	ND	744	30	3950	71
50	ARA_50	Bahiyara	Koilwar	SR	ND	0.15	1.2	ND	2.5	32	338	660	1412
51	ARA_51	Bahiyara	Koilwar	HP	ND	0.6	ND	ND	ND	6	16	ND	219
52	ARA_52	Kundeshwar	Behea	HP	ND	ND	ND	ND	ND	3	30	290	187
53	ARA_53	Suhiya	Shahpur	GR	4.8	0.9	3.2	ND	2.6	142	174	310	640
54	ARA_54	Ishwerpura (S)	Shahpur	HP	6.6	ND	ND	ND	ND	556	40	170	295
55	ARA_55	Suhiya	Shahpur	HP	18.7	0.2	10.3	ND	19.7	530	111	2670	3373
56	ARA_56	Suhiya	Shahpur	HP	1.3	0.1	0.3	ND	2.5	613	23	1200	442

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Location	Block	Source	As ppb	Cd ppb	Cu ppb	Ni ppb	Pb ppb	Mn ppb	Al ppb	Fe ppb	Zn ppb
57	ARA_57	Ishwerpura	Shahpur	HP	88.4	0.9	ND	ND	0.2	665	25	14620	788
58	ARA_58	Ishwerpura	Shahpur	HP	85.0	ND	ND	ND	3.0	848	30	740	872
59	ARA_59	Samaria Ojha Patti	Shahpur	HP	206.1	0.9	ND	ND	1.3	676	46	15000	56
60	ARA_60	Samaria Ojha Patti	Shahpur	HP	14.7	ND	ND	ND	ND	313	39	1190	57
61	ARA_61	Samaria Ojha patti	Shahpur	HP	1.9	0.3	7.0	ND	3.0	385	61	840	1943
62	ARA_62	Narinpur	Jagdishpur	HP	ND	0.01	ND	ND	ND	41	31	1110	5300
63	ARA_63	Behea Bazar	Behea	HP	ND	ND	ND	ND	ND	6	27	10	140
64	ARA_64	Ganj	Behea	HP	ND	ND	1.0	0.3	5.7	29	46	430	276
65	ARA_65	Jogibir	Behea	HP	ND	0.12	ND	ND	ND	21	26	1120	211
66	ARA_66	Dumaria	Shahpur	HP	4.2	ND	ND	ND	ND	698	15	380	99
67	ARA_69	Sarna	Shahpur	HP	2.1	ND	ND	ND	0.2	653	17	90	142
68	ARA_70	Chamarpur	Shahpur	HP	60.8	ND	ND	ND	ND	665	14	3220	810
69	ARA_71	Rajapur	Shahpur	HP	4.3	ND	ND	ND	ND	1057	18	70	125
70	ARA_72	Salempur	Ara	HP	9.8	ND	ND	ND	ND	136	15	740	354
71	ARA_73	Mauzampur	Barhara	GR	2.4	ND	0.4	ND	ND	70	149	120	227
72	ARA_74	Mauzampur	Barhara	HP	ND	ND	ND	4.7	1.2	1421	23	260	30

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Location	Block	Source	As ppb	Cd ppb	Cu ppb	Ni ppb	Pb ppb	Mn ppb	Al ppb	Fe ppb	Zn ppb
73	ARA_75	Narbirpur	Koilwar	HP	ND	ND	ND	ND	1.4	279	128	810	860
74	ARA_76	Nasarathpur	Sandesh	HP	ND	ND	8.8	ND	1.3	16	40	1370	305
75	ARA_77	Son River	Sandesh	SR	ND	ND	ND	ND	ND	14	216	220	40
76	ARA_78	Tirthkul	Sandesh	HP	ND	ND	1.1	ND	ND	11	42	310	314
77	ARA_79	Ahmad Chaktola	Sandesh	HP	0.1	ND	ND	ND	ND	3	34	290	55
78	ARA_80	Karbasen Ka tola	Agiaon	HP	ND	ND	ND	ND	ND	250	27	100	122
79	ARA_81	Sahar	Sahar	SR	ND	ND	ND	ND	ND	24	352	390	6
80	ARA_82	Sahar	Sahar	HP	12.6	ND	ND	ND	ND	2	24	270	6
81	ARA_83	Ekwari	Sahar	HP	1.1	ND	ND	ND	ND	ND	21	40	34
82	ARA_84	Chauriya	Agiaon	HP	ND	ND	ND	ND	1.4	63	236	2400	955
83	ARA_85	Belaur	Udwantnagar	HP	ND	ND	ND	ND	ND	10	14	120	64
84	ARA_86	Pipania	Udwantnagar	HP	ND	ND	ND	ND	1.7	22	39	330	1097
85	ARA_87	Bharara	Barhara	HP	ND	ND	ND	ND	0.5	273	124	810	872
86	ARA_94	Chhetni Ka Bag	Barhara	HP	10.7	ND	ND	ND	ND	329	21	1280	150
87	ARA_95	Bhagwanpur	Agiaon	HP	9.8	ND	ND	ND	ND	ND	6	ND	15
88	ARA_104	Nakhnaam Tola	Barhara	HP	9.2	ND	ND	ND	ND	0	9	ND	ND
89	ARA_105	Nakhnaam Tola	Barhara	HP	0.0	ND	ND	ND	1.5	160	7	ND	ND
90	ARA_106	Nakhnaam Tola	Barhara	HP	2.9	ND	ND	ND	0.5	413	8	ND	ND
91	ARA_107	Ghaziapur	Barhara	HP	39.9	ND	ND	ND	0.0	ND	7	ND	ND

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Location	Block	Source	As ppb	Cd ppb	Cu ppb	Ni ppb	Pb ppb	Mn ppb	Al ppb	Fe ppb	Zn ppb
92	ARA_108	Ghaziapur	Barhara	HP	0.3	ND	ND	ND	ND	490	10	ND	103
93	ARA_109	Ghaziapur	Barhara	HP	3.5	ND	ND	ND	0.8	ND	10	ND	ND
94	ARA_110	Damodarpur	Shahpur	HP	ND	ND	ND	ND	ND	ND	11	ND	14

HP= Hand pump, GR= Ganga river, SR= Son river

Table 5.6: Distribution of As and other heavy metals concentration during pre-monsoon in the study area.

S.No.	Sample Code	Source	As ppb	Al ppb	Cd ppb	Cu ppb	Ni ppb	Pb ppb	Mn ppb	Zn ppb	Fe ppm
1	B1	HP	67.9	57	ND	3	ND	ND	599	161	3.43
2	B2	HP	78.2	228	ND	10	ND	ND	452	381	3.17
3	B3	HP	10.6	48	ND	3	ND	12	322	150	1.30
4	B4	HP	3.5	51	1	5	ND	5	348	848	0.67
5	B5	HP	65.5	46	1	3	ND	ND	301	144	3.70
6	B6	HP	307.8	53	1	ND	ND	6	390	212	6.17
7	B7	HP	23.1	50	ND	4	ND	12	282	161	0.14
8	B8	HP	320.1	76	1	4	ND	ND	636	147	14.39
9	B9	HP	14.3	53	1	5	ND	ND	19	302	0.16
10	B10	HP	3.2	49	ND	2	ND	4	334	170	0.18
11	B11	HP	79.6	51	1	3	ND	6.5	277	163	3.61
12	B12	HP	4.5	51	ND	3	ND	ND	511	168	0.34
13	B13	HP	ND	36	ND	4	ND	ND	357	182	0.30
14	B14	HP	ND	35	ND	4	ND	ND	346	167	0.06
15	B15	G R	34.7	332	ND	3	ND	ND	158	202	0.58
16	B16	HP	36.6	47	ND	7	7	11.8	126	1687	0.19
17	B17	HP	336.6	57	1	ND	2	10	745	245	13.60
18	B18	HP	60.5	58	ND	3	ND	ND	207	214	3.55
19	B19	HP	22.8	302	ND	7	11	8	909	288	4.31
20	B20	HP	141.2	53	1	4	ND	8	624	196	5.53
21	B21	HP	56.3	54	ND	3	ND	7	140	208	2.75
22	B22	HP	3.8	54	ND	2	ND	ND	569	209	0.20
23	B23	HP	16.9	83	1	6	ND	12	525	2190	1.72
24	B24	HP	3.1	60	3	5	ND	6	490	143	0.20
25	B25	HP	147.8	60	1	4	ND	ND	330	183	0.30
26	B26	HP	56.2	49	1	0	ND	9	127	154	1.28

HP= Hand Pump, GR= Ganga River, SR= Son River

S.No.	Sample Code	Source	As ppb	Al ppb	Cd ppb	Cu ppb	Ni ppb	Pb ppb	Mn ppb	Zn ppb	Fe ppm
27	B27	HP	165.1	58	1	4	ND	6	503	201	6.81
28	B28	HP	286.4	69	1	3	ND	ND	587	167	8.25
29	B29	HP	204.7	75	1	2	ND	12	626	382	13.65
30	B30	HP	328.4	122	1	2	ND	8	782	199	3.10
31	B31	HP	8.1	48	ND	5	ND	12	470	151	0.11
32	B32	HP	3.5	37	1	3	3	9	89	140	0.23
33	B33	HP	18.9	80	ND	3	ND	ND	4	138	0.12
34	B34	HP	ND	58	ND	2	ND	8	8	174	0.23
35	B35	SR	ND	577	ND	5	ND	ND	37	169	0.75
36	B36	HP	11.4	39	1	3	ND	13	4	116	0.15
37	B37	HP	ND	64	2.7	4	ND	ND	2	154	0.10
38	B38	HP	ND	47	ND	2	4	12.2	306	128	0.12
39	B39	HP	72.2	43	1	ND	4	5	380	110	1.78
40	B40	GR	16.2	1171	1	6	ND	ND	132	141	1.76
41	B41	HP	5.3	70	1	1	ND	ND	1303	163	0.11
42	B42	HP	70.9	62	1	6	ND	12	324	1631	4.36
43	B43	SR	5.7	732	ND	6	2	ND	111	155	1.15
44	B44	HP	113.3	59	1	2	ND	ND	549	129	3.53
45	B45	HP	89.5	68	1	3	ND	ND	1221	250	6.96

HP= Hand Pump, GR= Ganga River, SR= Son River

Arsenic (As): Arsenic is usually present in natural waters at concentrations of less than 1-2 ppb. However, the arsenic concentration can be significantly elevated in groundwater, where there are sulfide mineral deposits and sedimentary deposits deriving from volcanic rocks. In the study area (covering entire Bhojpur district), concentration of arsenic in groundwater during post-monsoon season varies between ND to 206 ppb (Semaria ojha Patti of Sahpur block) with average 15 ppb. Figure 5.15 shows that about 30% of analysed ground water samples having As concentration above acceptable limit (10 ppb) and 8 % exceeding the permissible limit (50 ppb) of drinking water as prescribed by BIS (2012). The As concentration was almost negligible in river water, i.e. arsenic in Ganga water and Son water samples varies between 2 to 5 ppb and ND to 2 ppb respectively. On the other hand, during pre- monsoon sampling results from arsenic affected areas suggest that ∼66% of water samples are enriched with dissolved As concentrations >10 ppb, and it ranges from below detectable limit (BDL) to 337 ppb (average 78 ppb) (Table 5.6). About 22% GW samples shows marginally elevated As (ranging between 10-50 ppb) concentration in the study area, whereas about 44% of the samples exceeds the permissible limit of 50 ppb (Fig. 5.15). Arsenic in groundwater exhibited a wide spatial variation, even more than 100 times within a distance of 200 m and the similar observation has been reported by Saha D. (2008) for the GW (hand pump) of Bariswan village of Bhojpur district. The elevated As concentration mainly from Sahapur and Barahara block of northern part of the study area located in younger alluvium of Ganga flood plain has been observed. The northern part of the study area is mostly comprised of fluvial deposits, unconsolidated sand gravels, silts and clays. These flood plains are having numerous oxbow lakes which is filled with fine-grained suspension-load sediment rich in organic matter act as an efficient factory for the mobilization of arsenic by microbial-mediated reductive dissolution. So, the lithology and the associated changes in the redox potential may be the reasons for the elevated arsenic concentration in northern part of the study area. Spatial distribution map of arsenic (Fig. 5.16) is showing that northern part of the study area associated with Ganga alluvium plain is more arsenic affected in comparison with southern part of the district. The lowest concentration of As has been found out in Sandesh block whereas highest values observed in Samariaohja Patti village of Barahara block.

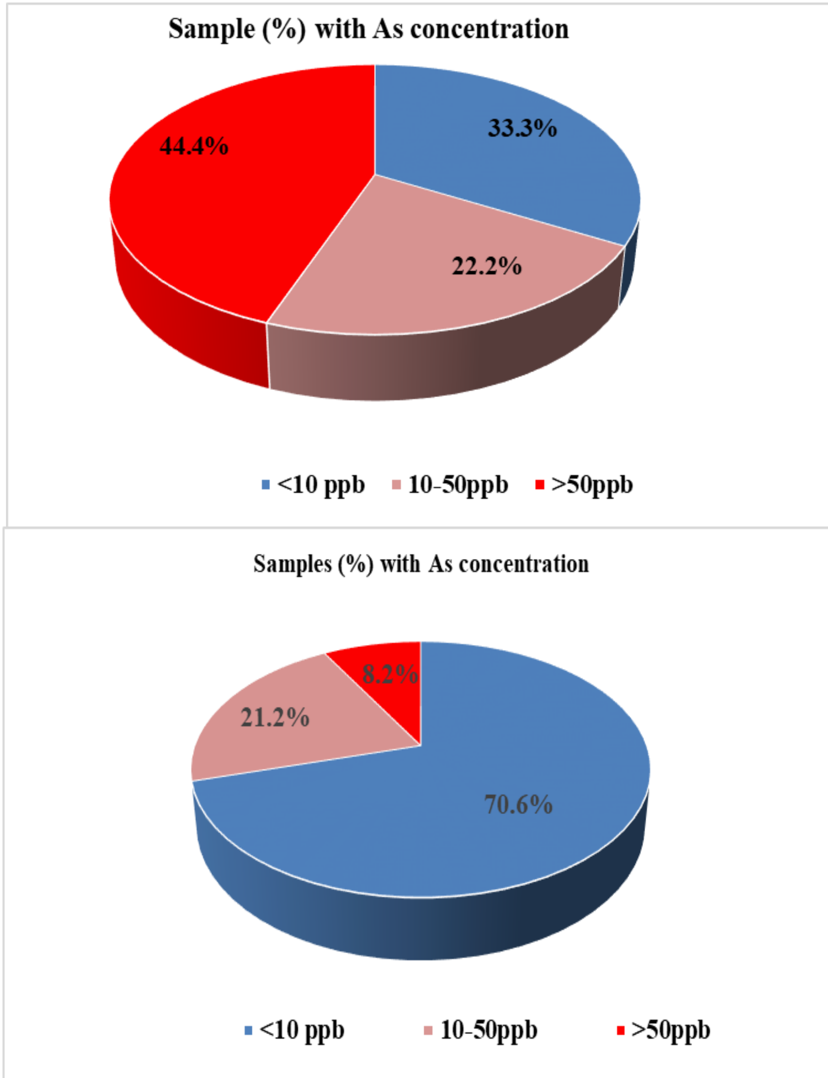


Figure 5.15: Pi-diagram showing % of ground water samples affected with Arsenic in the study area during (a) post monsoon (a) pre monsoon seasons (arsenic affected area).

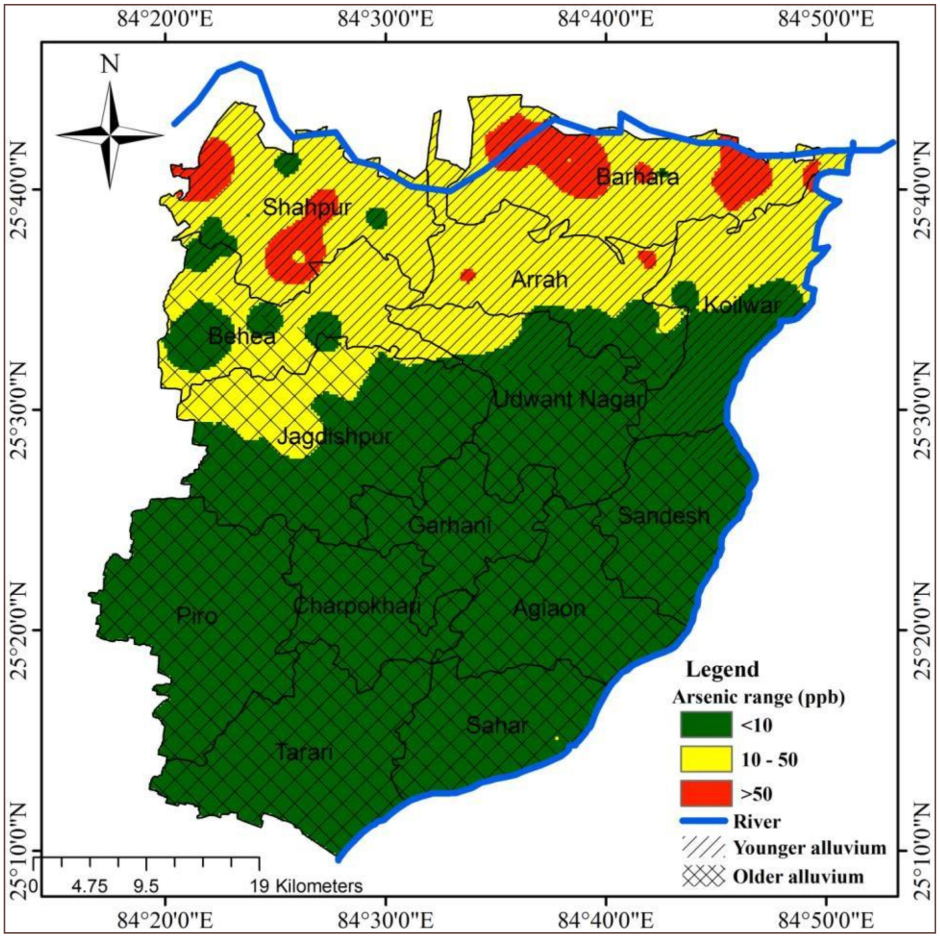


Figure 5.16: Spatial distribution of As concentration in the study area

The groundwater samples collected during sampling were generally from hand pumps with depth ranging from 15 to 80 m because of potential sand zones at shallow depth. Depth vs. As conc. cross-plot of samples from study area reveals a rapid decrease in As conc. beyond 60 m bgl (Fig. 5.17). It implies that only upper aquifer is contaminated by As.

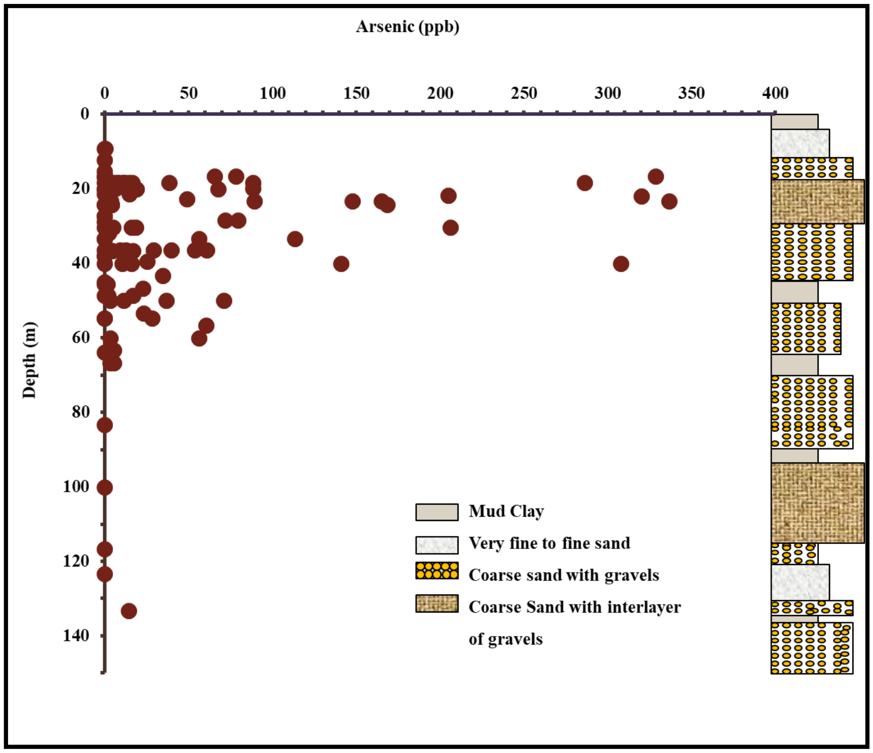
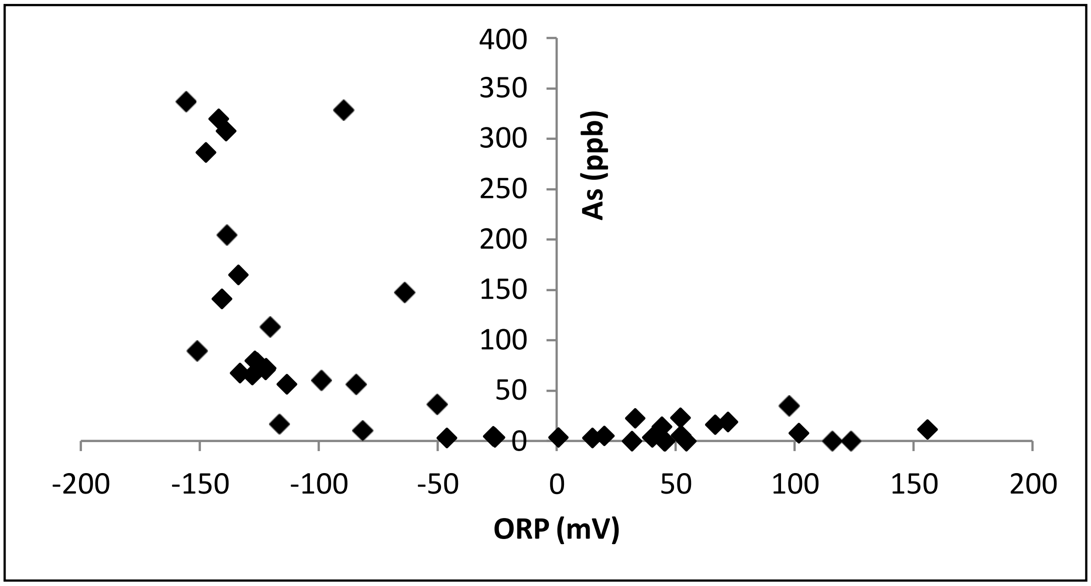
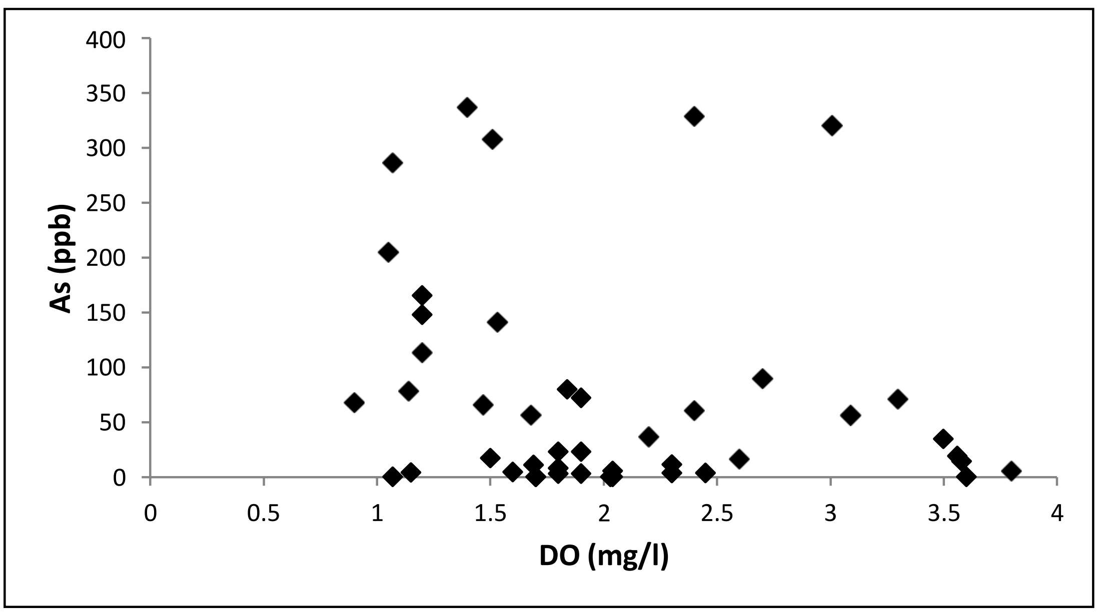
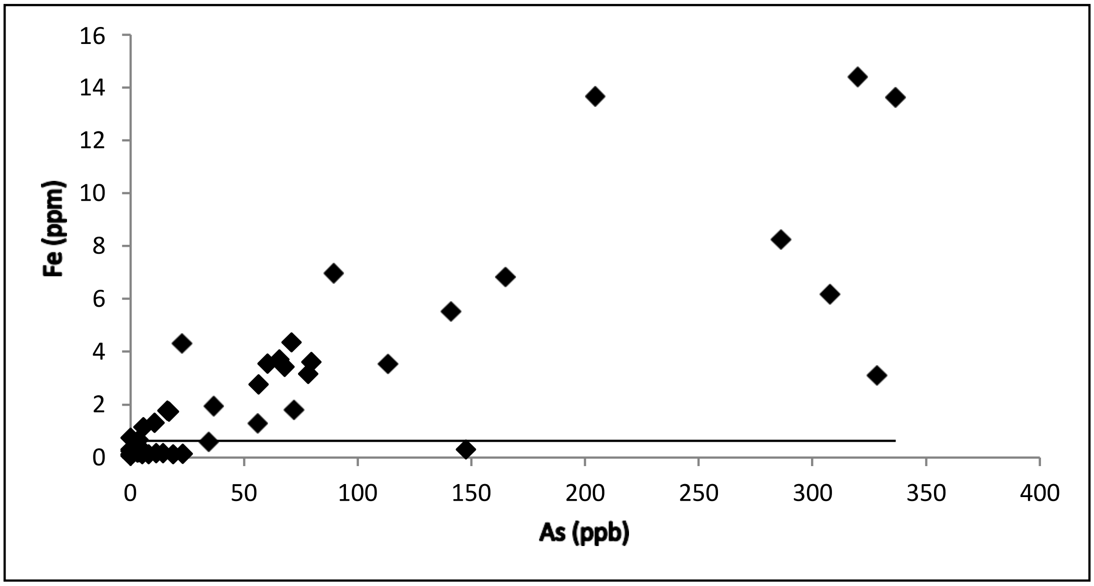


Figure 5.17: Depth wise variation of As with geological profile

The parameters such as oxidation-reduction potential (ORP), Fe, Mn, NO_3 and SO_4 are the main redox parameters that control the release of As in groundwater (Zhou et al., 2017). The good correlation between As and ORP (0.61) suggest a redox-dependent mobilization played an important role in As liberation. Fe is positively correlated with As, (0.627), but As shows a weak positive correlation with Mn (Fig. 5.18), which indicatethat As might mobilized from dissolution/desorption from iron hydroxides in the sediment (Chakraborty et al., 2015). Some authors (Das et al., 1996) have proposed that As could be mobilized from the oxidation of As-enriched pyrite, and some others (Bhattacharya et al., 1997; Zheng et al., 2004) proposed the importance of reductive dissolution of metal (Fe/Mn) oxide/hydroxide and subsequent release of the adsorbed As, in the process of its mobilization. The As showed a weak correlation with SO_4 (0.152) and NO_3 (0.113). The weak correlation of SO_4 and NO_3 with arsenic indicate redox dependant mobilization of As (Ali et al., 2019). Fig. 5.18 shows that As concentration is very much dependant on redox potential and it is evidently noticeable that arsenic is high when ORP is negative and DO is less, reflecting the occurrence of arsenic in reducing conditions. Further, ORP value was found more negative in the pre-monsoon season followed by post-monsoon and monsoon season. The arsenic is less in the monsoon season and high in the pre-monsoon season, with a larger negative value of ORP. Similar observations on seasonal arsenic variation were also reported by Saha and Sahu (2015) for the study of the middle Ganga plain.







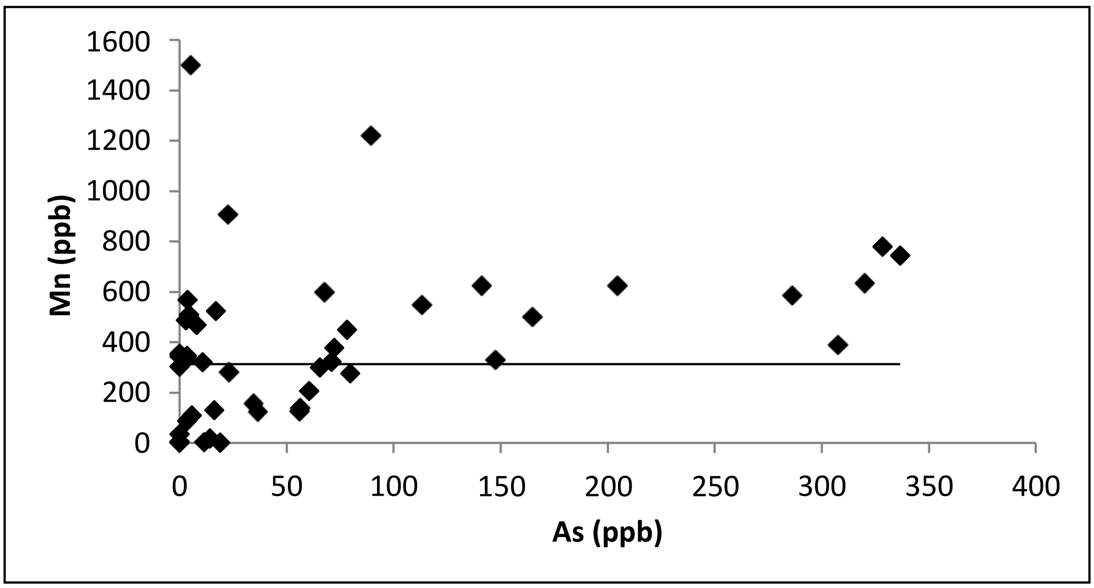


Figure 5.18: Scatter plot between arsenic and (a) ORP, (b) DO, (c) Fe and (d) Mn

The extent of arsenic variation may vary significantly season-wise in the same sampling location. Numerous studies conducted worldwide reported that significant seasonal variation of arsenic with less or no temporal change in arsenic concentration in the same sampling location (Savarimuthu et al., 2006; Ayotte et al., 2015; Zkeri et al., 2018). The long-term and seasonal variation are important for epidemiological research and to develop a mitigation strategy. In the present case, groundwater was monitored to analyze the changes in arsenic, iron and other trace metals concentration during different seasons in a year (2019) in hand pumps of the study area (sampling locations are shown in Fig. 4.1). In the present case, significant seasonal variation in arsenic concentration in water samples was noted, particularly for the samples collected from the N-E part of the study area, while the samples from the central part represented no arsenic in any season (Fig. 5.16). The arsenic concentration is observed more in pre-monsoon seasonas compared to post monsoon season (Fig. 5.19). There are several reasons for seasonal changes of arsenic concentration in groundwater, such as dilution effect due to recharge, seasonal changes in redox conditions, pumping rates, movement of groundwater flow and water table depths (Nadakavukaren et al., 1984; Tareq et al., 2003; Shih 2005). For the present case, variation in arsenic concentrations in groundwater are supposed to be due to the dilution effect and changes in redox conditions, which may cause desorption of arsenic from metal oxides.

Iron (Fe): Iron in trace amounts is essential for nutrition. High concentrations of iron generally cause inky flavor, bitter and astringent taste to water. Groundwater containing soluble iron remain clear while pumped out, but exposure to air causes precipitation of iron due to oxidation, with a consequence of rusty color and turbidity. The objection to iron is not due to health reason though there is a taste and odour problem. The concentration of Fe in groundwater, Ganga and Son river water samples of the study area varies between ND to 15 ppm, 0.12 to 0.31 ppm and 0.2 to 0.66 ppm with average concentration 1.5, 0.22 & 0.4 ppm respectively during post monsoon whereas in pre- monsoon, the Fe concentration ranges from 0.06 to 14.4 ppm with average concentration 2.9 ppm in groundwater samples. The Bureau of Indian Standards has recommended 0.3 mg/l as the as the acceptable limit for iron in drinking water. It is evident from the results that ~29% and 69% of groundwater samples exceeding the acceptable limit for drinking water prescribed by BIS (2012) during post monsoon and pre monsoon seasons respectively. Fig. 5.19 shows the seasonal variation of Fe in arsenic affected areas and in most of the samples, Fe concentration is more in pre-monsoon as compared to post- monsoon season.

Manganese (Mn): Manganese is naturally occurring in many surface water and groundwater sources, particularly in anaerobic or low oxidation conditions. Manganese exceeding 0.1 mg/l in water supplies causes an undesirable taste in beverages and stains sanitary ware and laundry. The presence of manganese in drinking-water may lead to the accumulation of deposits in the distribution system. The concentration of manganese in groundwater, Ganga water and Son river water varies between ND to 6.2 mg/l, 0.069 to 0.14 mg/l and 0.014 to 0.153 mg/l respectively during post monsoon whereas in pre-monsoon, ground water samples concentration of manganese ranges from 2.1 to 1303 ppb, with mean conc. 411 ppb.

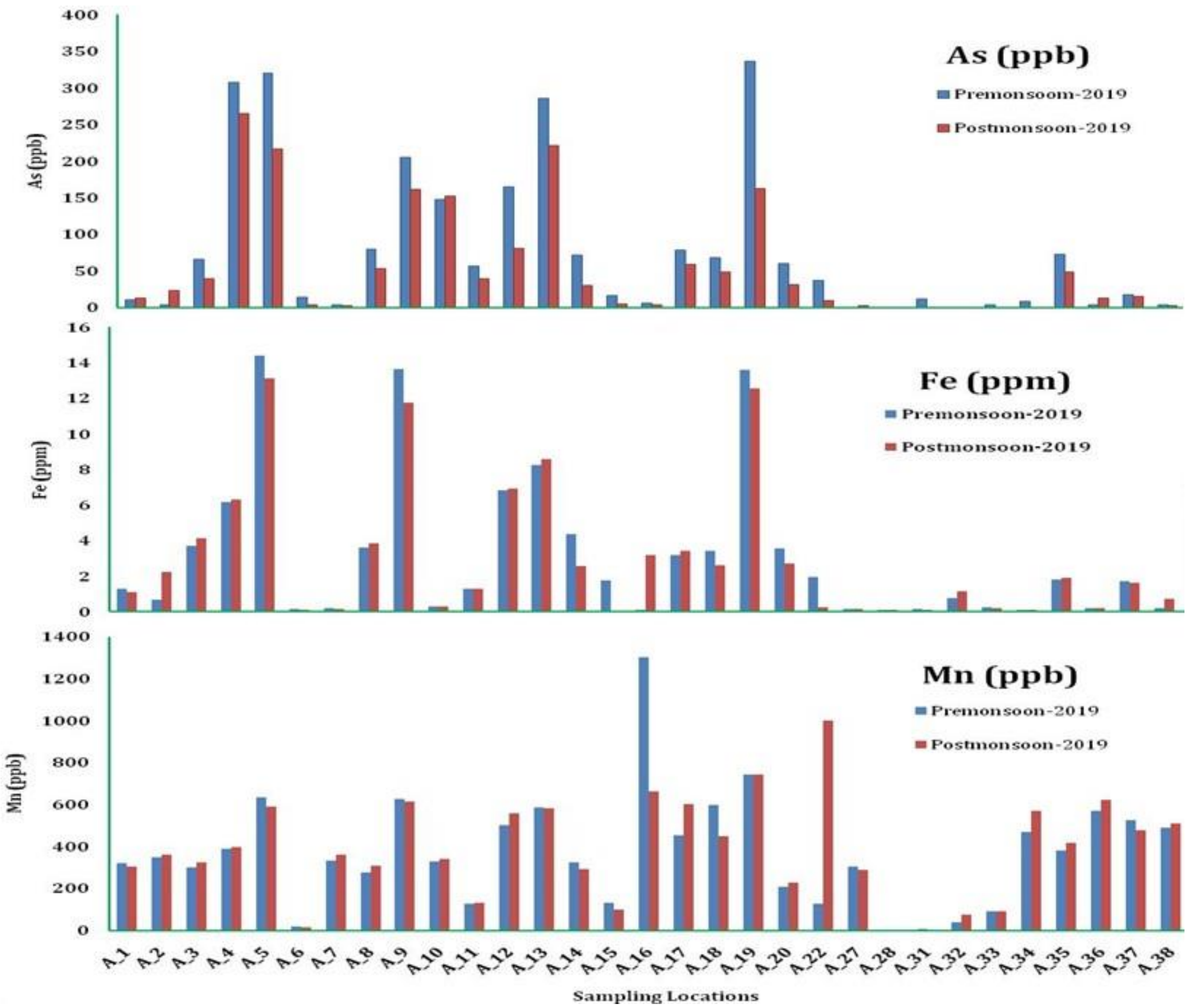


Figure 5.19: Temporal variation (pre and post monsoon season, 2019) of arsenic, iron and manganese

Cadmium (Cd): Cadmium is a nonessential non-beneficial element and known to have a high toxic potential. Cadmium may enter into the environment from a variety of industrial applications, including mining and smelting, electroplating, and pigment and plasticizer production. The concentration of cadmium in groundwater, Ganga and Son rivers do not show significant variation. Concentration of cadmium varies between ND to 0.9 ppb for all types of water sources during post monsoon whereas in pre monsoon Cd concentration varies from BDL to 2.7 ppb in groundwater samples. These concentrationsare less than permissible limit (3 ppb) for the drinking water as prescribed by BIS-2012.

Copper (Cu): Copper is both an essential nutrient and in higher concentration it becomes drinking-water contaminant. It is used to make pipes, valves and fittings and is present in alloys and coatings. Beyond 0.05 ppm the water imparts astringent taste and cause discoloration and corrosion of pipes, fittings and utensils. Recent studies have delineated the threshold for the effects of copper in drinking-water on the gastrointestinal tract, but there is still some uncertainty regarding the long-term effects of copper on human health. The concentration of copper in groundwater, Ganga river and Son river water samples of the study area varies between ND to 19 ppb, ND to 3.2 ppb and ND to 3.1 ppb during post monsoon whereas in pre-monsoon, ground water samples concentration of copper ranges from ND to 10 ppb, with an average value 4 ppb. The Bureau of Indian Standards has recommended 0.05 ppm as the acceptable limit and 1.5 ppm as the permissible limit in the absence of alternate source (BIS, 2012). In the study area, all the samples fall in the acceptable limit of 0.05 ppm.

Nickel (Ni): Nickel is released to the environment from the burning of fossil fuels and waste discharge from electroplating industries. The concentration of nickel in groundwater, Ganga water and Son river water samples of the study area varies between ND to 5 ppb, not detected in Ganga river and ND to 4.4 ppb in Son river during post monsoon whereas in pre-monsoon samples concentration of Ni ranges from BDL to 11 ppb, with an average value 4 ppb. The prescribed acceptabe limit for Ni in drinking wateris 20 ppb and the concentration of Ni are well within the permissible limit, and only one ground water sample from Tenduuni village of Jagdishpur block exceeded the permissible limit during pre-monsoon season.

Lead (Pb): Lead is the most common of the trace metals and is mined widely throughout the world. It is used principally in the production of lead-acid batteries, solderand alloys. The organic lead compounds tetraethyl and tetra methyl have been used extensively as antiknock and lubricating agents in petrol. Lead is rarely present in drinking water as a result of its dissolution from natural sources; rather, its presence is primarily from corrosive water effects on household plumbing systems containing lead inpipes, solder, fittings or the service connections. Exposure to lead is associated with a wide range of effects, including various neuro developmental effects, mortality (mainly due to cardiovascular diseases), hypertension, impaired fertility and adverse pregnancy outcomes. The concentration of Pb in groundwater, Ganga and Son rivers water samples of the study area varies between ND to 20 ppb (Suhiya village), ND to 2.6 ppb and ND to 2.5 ppb respectively during post monsoon whereas in pre-monsoon lead ranges from ND to 13 ppb in ground water samples. It is evident from the results that almost all the analysed samples are falling within the acceptable limit as prescribed by BIS, 2012.

Aluminum (Al): Aluminum is the most abundant metallic element and constitutes about 8% of Earth's crust. High residual concentrations may ensure undesirable color and turbidity. There is little indication that orally ingested aluminum is acutely toxic to humans despite the widespread occurrence of the element in foods, drinking-water and many antacid preparations. It has been hypothesized that aluminum exposure is a risk factor for the development or acceleration of onset of Alzheimer disease in humans. The concentration of Al in groundwater, Ganga and Son river water samples varies between 5.7 to 235 ppb, 149 to 185 ppb and 210 to 352 ppb respectively in the entire district of Bhojpur during post monsoon sampling whereas in pre-monsoon Al ranges from 35 to 331 ppb in ground water samples. The Bureau of Indian Standards has recommended 0.03 ppm as the acceptable limit and 0.20 ppm as the permissible limit for drinking water. It is evident from the results that ~25 % samples from the study area exceeded the acceptable limit and only 2 samples (Gajrapur and Chauriya village) exceeded the permissible limit during post monsoon seasons while in 13.33% exceeded the permissiblelimit for drinking purpose.

5.3. Suitability of water for irrigation purposes

5.3.1 Electrical Conductivity (EC) and Sodium Percentage (Na %)

EC and sodium concentration are very important in classifying irrigation water. Water used for irrigation always contains measurable quantities of dissolved substances as salts (Kumar et al., 2021c). The dissolved solids originate from the weathering of the rocks and soils and from the dissolving of lime, gypsum and other salt sources as water flows over or percolate through aquifer. The salts, besides affecting the growth of the plants directly, also affect soil structure, permeability and aeration, which indirectly affect plant growth. The sodium percentage (Na %) in the water samples of sub-surface water is calculated by the equation:

$$Na\,\% = \frac{(Na + K)}{(Ca + Mg + Na + K)} * 100$$

where Na, Ca and Mg concentrations is in milli-equivalents per litre.

The sodium percentage in the study area ranges between 10-59 % and 12-62 % for post-monsoon and pre-monsoon samples respectively. The high percentage of Na causes deflocculating and impairment of the tilth and permeability of soils. As per the Indian Standard (ISI 1993), maximum sodium of 60% is recommended for irrigation water. Plot of analytical data on Wilcox (1948) diagram relating EC and Na % shows that all of groundwater and river samples of the study area are falling in excellent to permissible quality category (Fig. 5.20) which can be used for irrigation purposes.

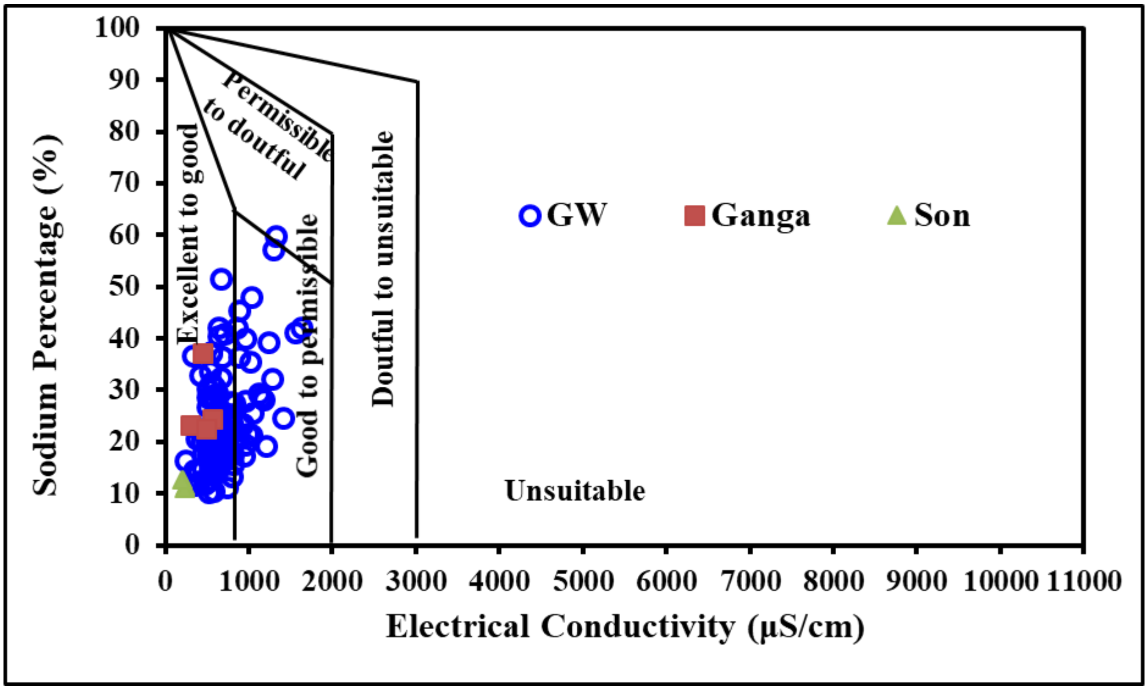


Figure 5.20: Plot of sodium percent (%Na) vs electrical conductivity (EC)

5.3.2 Alkali and salinity hazard (SAR)

The total concentration of soluble salts in irrigation water can be expressed as low (EC =<250 µS /cm), medium (250-750 µS /cm), high (750-2250 µS/cm) and very high (2250-5000 µS/cm) salinity zone. High salt concentration (high EC) in soil extract leads to formation of saline soil, a high sodium concentration leads to development of an alkaline soil. Excessive solutes in irrigation water are a common problem in semi-arid areas where water loss through evaporation is maximal. Salinity problem encountered in irrigated agriculture are most likely to arise where drainage is poor. This allows the water table to rise close to the root zone of plants, causing the accumulation of sodium salts in the soil solution through capillary rise following surface evaporation of water. The sodium or alkali hazard in the water for irrigation is determined by the absolute and relative concentration of cations and is expressed in terms of sodium adsorption ratio (SAR). It can be estimated by the formula:

$$\mathrm{SAR} = \frac{Na}{\sqrt[2]{\left(\frac{Ca+Mg}{2}\right)}}$$

where Na, Ca and Mg concentrations is in milli-equivalents per litre.

There is a significant relationship between SAR values of irrigation water and the extent to which sodium is absorbed by the soils. If water used for irrigation is high in sodiumand low in calcium, the cation-exchange complex may become saturated with sodium. This can destroy the soil structure due to dispersion of the clay particles. The calculated value of SAR in the study area ranged from 0-3.5 meq/l in the groundwater samples. 69%of samples fall in good category and 31% fall in fair category as per SAR and EC based classification (Table 5.7).

Table 5.7: Irrigation waters classification based on SAR and EC values

SAR	**water Category**	**Sample (%)**	**EC µS /cm**	**water Category**	**Sample (Dec/Jan-19)**	**Sample (May-19)**
0-10	Excellent (S-1)	100%	<250	Low (C-1)	0.0%	Nil
10-18	Good (S-2)	0%	250-750	Medium (C-2)	71.1%	68.89%
18-26	Fair (S-3)	0%	750-2250	High (C-3)	29.9%	31.11%
>26	Poor (S-4)	0%	>2250	Very High (C-4)	0.0%	Nil

The plot of data on the US salinity diagram, in which the EC is taken as salinity hazard and SAR as alkalinity hazard, shows that almost none of the samples are falling in C1S1, C4S2 & C4S4 zone while maximum water sample falling in C2S1 (68.8% -71.1%), C3S1(31.11-29.9%) section which indicating medium to high salinity and medium alkali water. (Fig. 5.21)

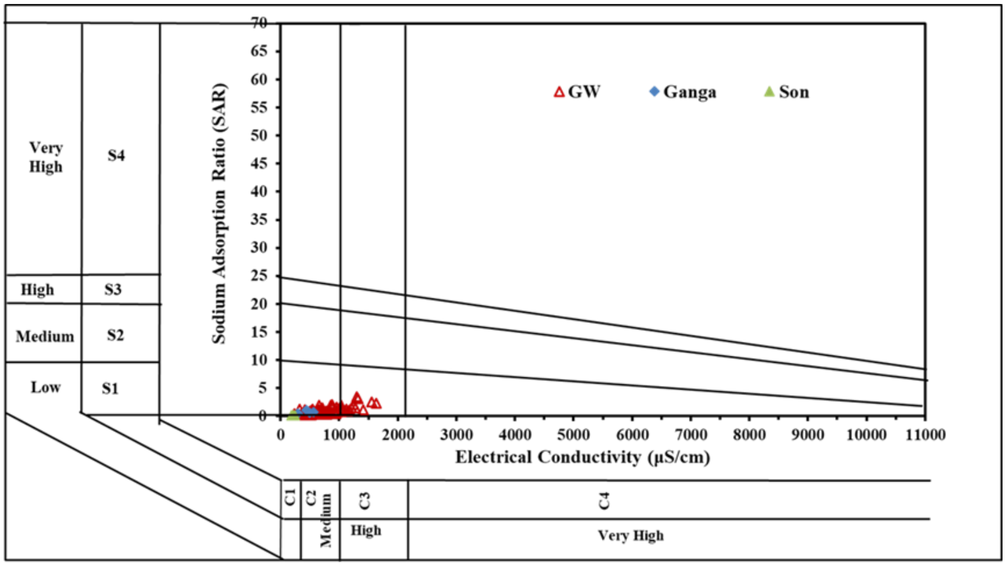


Figure 5.21: Salinity diagram for classification of irrigation water

5.4 Stable isotopes ($\delta^{18}O$, $\delta^{2}H$) in groundwater

The groundwater, river water and few precipitation samples were analysed for the isotopic ($\delta^{18}O$, and $\delta^{2}H$) compositions to identify the zones of recharge, and recharge sources in the study area. The primary recharge sources of groundwater are meteoric water, rivers, and irrigation canals. The groundwater samples exhibit $\delta^{18}O$ values in the range of -6.89 to -3.89 ‰ with an average of -5.64 ‰ and $\delta^{2}H$ from -50.17 to -33.70 ‰ with an average of -43.48 ‰ respectively. The isotopic values of the Ganga river samples(n = 3) varies from -5.83‰ to -5.75 ‰ for $\delta^{18}O$ and for $\delta^{2}H$ varies from -45.90 ‰ to -42.67 ‰ whereas the isotopic values of the Son river samples (n = 4) varies from -4.44 ‰ to -2.36 ‰ for $\delta^{18}O$ and -33.48 ‰ to -26.81 ‰ for $\delta^{2}H$. The cross-plot of the stable isotopes, as shown in Fig. 5.22 (a), reveals that groundwater samples are falling over Local Meteoric Water line (LWML developed by Kumar et al., 2010 for Patna station which is 50 km from the study area). The slope and intercept of the groundwater regression line ($\delta^{2}H = 6.10*\delta^{18}O - 7.00$, ($r^2$=0.95)) are less than those of the LMWL ($\delta^{2}H = 7.8*\delta^{18}O +3.02$, ($r^2$=0.98)), indicating the important effect of evaporative enrichment on groundwater (Wassenaar et al., 2011). The Son river is highly enriched in isotopic signatures as compare to the Ganga river, indicating highly enriched source or evaporation of the water during the travel from the Vindhyan mountains. The spatial variation of $\delta^{18}O$ reveals that there is a distinct isotopic difference between groundwater samples from the proximity of Ganga and Son rivers. The Ganga river has an average $\delta^{18}O$ value of -5.78‰ whereas the isotopic value for Son river is -3.17%. Similarly, the groundwater samples for both the river water region ranges close to its river accompanying it, indicating depleted groundwater near to Ganga river and enriched groundwater close to Son river. We infer that the enriched value of groundwater samples close to Son river is due to recharge through the Son river, while the groundwater close to Ganga is contributing to Ganga river. This is also corroborating from the groundwater flow direction which is toward the Ganga river.

The data deviating from the LMWL is generally termed as 'd-excess' and is defined as d-excess = $\delta^2H - 8*\delta^{18}O$ (Pant et al., 2021a). The cross plot between $\delta^{18}O$ and d-excess (Fig. 5.22 b) indicates the origin of groundwater is local precipitation with low to high evaporation enrichment effect. The isotopic signature of the groundwater also indicates the vertical mixing of groundwater from the irrigation return flow or other sources and similar findings were also made by Mukherjee et al., 2018 for lower Ganga plain.

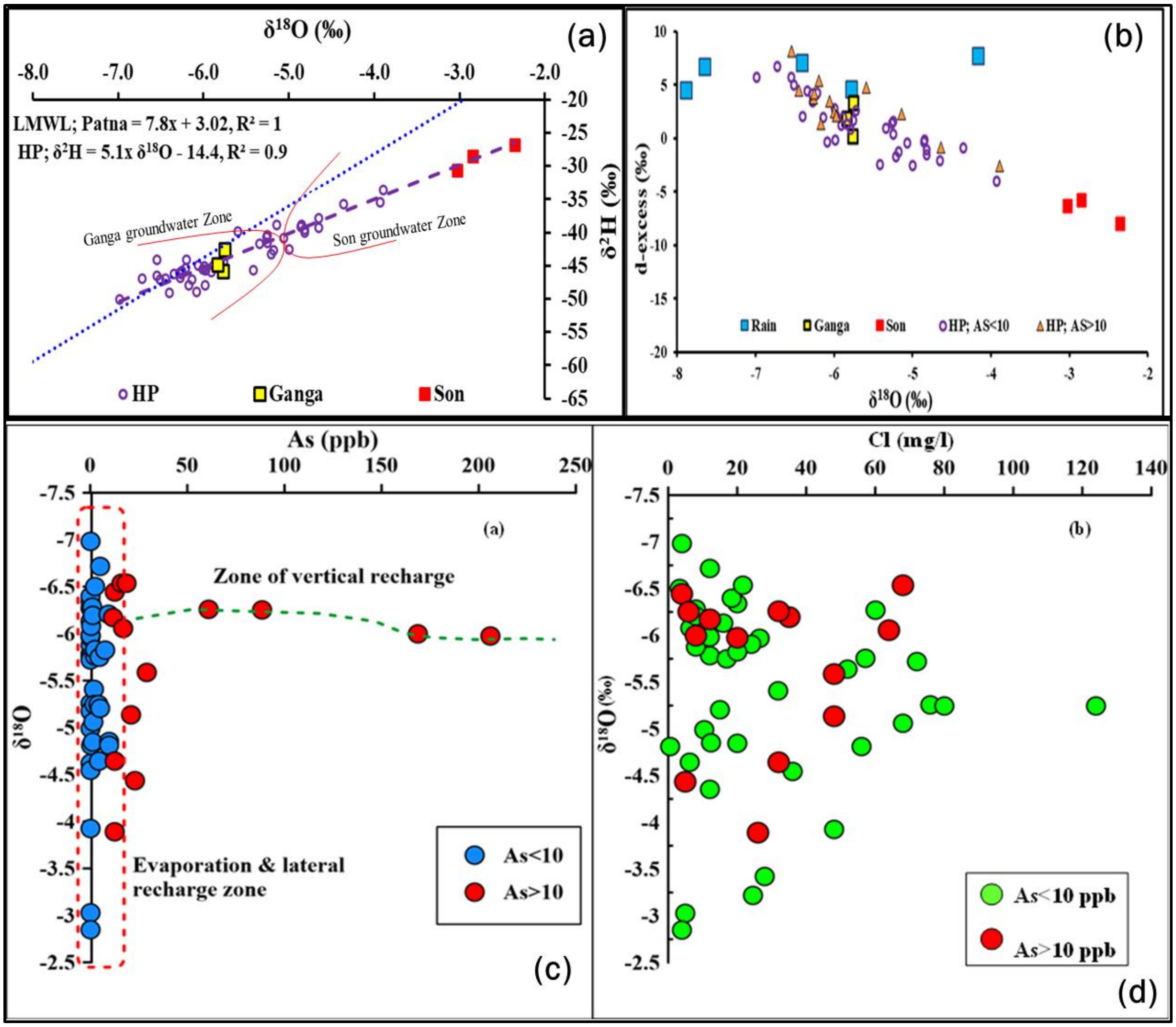


Figure 5.22: Isotopic characterisation of the ground water of the study area (a) groundwater samples are falling over Local Meteoric Water line (b) The cross plot between $\delta^{18}O$ and d-excess (c) fast vertical recharge (d) The bivariate plot between Cl and $\delta^{18}O$.

The groundwater samples having isotopic signatures around -6 ‰ indicating fast vertical recharge (Fig. 29 (c)) is having As > 10 µg/L, whereas groundwater samples with As < 10 µg/L show variation in $\delta^{18}O$ signatures due to evaporation and lateral recharge mechanism (Mushtaq et al., 2018). High As concentrations in groundwater infers that recharge from meteoric water and evaporation might be contributing towards As release from aquifer matrix to the groundwater of the study area (Mushtaq et al., 2018), which may result in enabling the desorption reaction of As from the surfaces of oxide in mineral. The bivariate plot between Cl and $\delta^{18}O$ (Fig. 29(d)) shows that groundwater samples having low As (<10 µg /L) and high As (>10µg/L) concentration indicating large lateral variation in the Cl values with that of changing $\delta^{18}O$ values.

5.5 Sediments Characterization

5.5.1 Sediment textural analysis

Grain size analysis determines the relative amounts of sand, silt and clay in a soil. These size fractions are the mineral component of a soil and determine soil texture. Soil texture is an inherent soil quality property that has a major influence on several other properties that influence agricultural potential. In the present study, sediments samples were collected from eight boreholes and their depth varies in the range 24.4 -42.67 m (Table 5.8). Lithological profile largely represents a sandy channel-fill deposits with clayey silty over bank deposit at the top indicting a fluvial environment of deposition. The upper 3.05-6 m of the sequence is light grey to yellowish grey in color while the lower part is grey to dark grey at maximum drilling sites except one site situated along Son River where lithology suggest presence of stiff brownish slity/sandy-clay. Examination of sediment samples in hand specimen show that the sands are fine to medium grained in size and predominantly composed of quartz with significant amount of mica, minor feldspars (potassium and plagioclase) and ferromagnesian minerals.

Table 5.10 describing the sand, silt and clay percentages in sediment collected during drilling of piezometers at different locations in the study area. Grain size analysis results reveal that clay contents in the soils samples (upto depth 42.67 m) ranges from 0.1 to 19.2%, silt and sand contents has wider ranges of volume percent; silt contents ranges from 1.3 to 86.8%; while sand contents ranged from 3.0 to 98.7% and gravel percentage varies from 0.0 to 11.3% in the study area. However, coarse size fractions increases with depth in these soils with reduction in fine size fractions. Based on textural classificationof soil samples, the soil/sediment of the study area are mainly Silty type. Generally, the clay content is more at upper depth and with increasing depth % of silt increases and finally when aquifer starts percentage of sand is maximum.

Table 5.8: Grain size distribution of the sediment in the study area

S.N	Sample code	Location	Sample Depth (m)	Gravel (%)	Clay (%)	Sand (%)	Silt (%)	Soil Type
1	Mau_S_1	Mauzampur	0-1.52	0.5	5.7	24.1	69.7	Silt Loam
2	Mau_S_2		3.05-4.6	0.3	1.3	50.9	47.5	Sandy Loam
3	Mau_S_3		6.1-7.6	1.2	14.4	5.3	79.1	Silt Loam
4	Mau_S_4		9.14-10.7	0.0	8.9	4.3	86.8	Silt
5	Mau_S_5		12.2-13.7	0.9	4.4	9.9	84.8	Silt
6	Mau_S_6		15.2-16.8	0.2	8.1	6.8	84.9	Silt
7	Mau_S_7		18.3-19.8	0.0	0.9	86.7	12.4	Loamy Sand
8	Mau_S_8		21.3-22.9	0.1	0.5	92.3	7.1	Sand
9	Mau_S_9		22.9-24.4	0.0	0.3	92.2	7.5	Sand
10	Ish_S-1	Ishwerpura	0-1.52	0.1	3.4	21.0	75.5	Silt Loam
11	Ish_S-2		3.05-4.6	0.7	3.5	14.6	81.2	Silt
12	Ish_S-3		6.1-7.6	0.0	0.0	86.9	13.1	Sand
13	Ish_S-4		7.6-9.14	0.0	1.3	78.8	19.9	Loamy Sand
14	Ish_S-5		9.14-10.7	0.0	3.3	37.5	59.1	Silt Loam
15	Ish_S-6		12.2-13.7	0.0	9.7	8.5	81.8	Silt
16	Ish_S-7		13.7-15.2	0.0	4.1	61.3	34.6	Sandy Loam
17	Ish_S-8		15.2-16.8	0.0	4.1	24.1	71.8	Silt Loam
18	Ish_S-9		18.3-19.8	0.2	2.9	59.2	37.8	Sandy Loam
19	Ish_S-10		21.3-22.9	0.2	0.1	96.5	3.3	Sand
20	Ish_S-11		22.9-24.4	0.0	0.0	98.7	1.3	Sand
21	Sim_A_1	Simariya_A	0-1.52	0.0	13.3	7.3	79.4	Silt Loam
22	Sim_A_2		3.05-4.6	0.3	10.6	11.0	78.1	Silt Loam
23	Sim_A_3		6.1-7.6	0.1	11.6	5.5	82.8	Silt
24	Sim_A_4		9.14-10.7	0.2	16.3	3.0	80.6	Silt
25	Sim_A_5		12.2-13.7	1.6	0.6	93.9	3.9	Sand
26	Sim_A_6		15.2-16.8	0.1	0.4	95.0	4.5	Sand
27	Sim_A_7		18.3-19.8	0.3	0.4	95.1	4.2	Sand
28	Sim_B_1	Simariya_B	0-1.52	0.4	7.3	8.2	84.1	Silt
29	Sim_B_2		3.05-4.6	0.7	6.5	10.2	82.5	Silt
30	Sim_B_3		6.1-7.6	0.6	5.9	7.6	85.9	Silt
31	Sim_B_4		9.14-10.7	0.2	15.0	3.0	81.8	Silt
32	Sim_B_5		12.2-13.7	0.0	9.6	6.3	84.0	Silt
33	Sim_B_6		15.2-16.8	2.4	0.9	88.2	8.6	Poorly gravelled Sand
34	Sim_B_7		18.3-19.8	0.3	0.5	92.6	6.5	Sand

S.N	Sample code	Location	Sample Depth (m)	Gravel(%)	Clay (%)	Sand (%)	Silt (%)	Soil Type
35	Sim_B_8		21.3-22.9	2.9	0.7	89.2	7.2	Poorly gravelled Sand
36	Sim_B_9		24.4-25.9	0.1	0.2	93.9	5.9	Sand
37	Sim_B_10		27.4-29	0.2	0.2	96.4	3.2	Sand
38	Sim_B_11		30.5-32	0.3	0.1	86.2	7.4	Sand
39	Sim_B_12		33.5-35.1	11.3	0.4	85.8	2.6	Sand with gravelled
40	Sim_B_13		36.6-38.1	0.2	0.1	94.8	5.0	Sand
41	Sim_B_14		39.6-41.1	3.1	0.1	94.9	2.0	Sand
42	Sim_B_15		41.1-42.7	1.3	0.1	96.5	2.1	Sand
50	Suh_S_1	Suhiya	0-1.52	0.4	3.3	72.2	24.2	Sandy Loam
51	Suh_S_2		3.05-4.6	0.0	0.0	91.3	8.7	Sand
52	Suh_S_3		6.1-7.6	0.0	0.0	97.7	2.3	Sand
53	Suh_S_4		9.14-10.7	0.2	0.0	84.9	14.9	Loamy Sand
54	Suh_S_5		12.2-13.7	0.0	0.0	91.8	8.2	Sand
55	Suh_S_6		13.7-15.2	0.1	0.0	96.6	3.2	Sand
56	Suh_S_7		16.7-18.3	1.3	0.6	93.0	5.1	Sand
57	Suh_S_8		19.8-21.3	2.5	1.1	88.7	7.6	Poorly Gravelled Sand
58	Suh_S_9		22.9-24.4	0.8	0.5	95.5	3.3	Sand
59	Sirs_S_1	Sirsiyan	0-1.52	1.1	6.7	11.0	81.2	Silt
60	Sirs_S_2		3.05-4.6	0.3	9.6	6.8	83.3	Silt
61	Sirs_S_3		6.1-7.6	0.2	10.5	9.4	79.9	Silt
62	Sirs_S_4		9.14-10.7	3.2	6.5	8.5	81.7	Silt
63	Sirs_S_5		12.2-13.7	0.2	10.0	11.1	78.7	Silt Loam
64	Sirs_S_6		15.2-16.7	0.1	0.3	92.8	6.8	Sand
65	Sirs_S_7		18.3-19.8	0.1	0.7	72.0	27.2	Loamy Sand
66	Sirs_S_8		21.3-22.9	0.1	0.1	95.0	4.8	Sand
67	Sirs_S_9		22.9-24.4	0.0	0.2	95.6	4.2	Sand
68	Bali_S_1	Baligaon	0-1.52	0.7	5.3	22.4	71.5	Silt Loam
69	Bali_S_2		3.05-4.6	0.7	1.3	24.8	73.2	Silt Loam
70	Bali_S_3		6.1-7.6	0.0	0.4	94.1	5.5	Sand
71	Bali_S_4		9.14-10.7	2.4	0.3	89.8	7.6	Poorly Gravelled Sand

S.N	Sample code	Location	Sample Depth (m)	Gravel(%)	Clay (%)	Sand (%)	Silt (%)	Soil Type
72	Bali_S_5		12.2-13.7	1.2	0.3	94.8	3.7	Sand
73	Bali_S_6		15.2-16.7	0.0	0.1	96.2	3.6	Sand
74	Bali_S_7		18.3-19.8	1.3	1.8	47.3	49.7	Silt Loam
75	Bali_S_8		21.3-22.9	1.3	0.5	81.7	16.5	Loamy Sand
76	Bali_S_9		22.9-24.4	3.7	0.1	93.7	2.6	Poorly Gravelled Sand
77	Andh_S_1	Andhari	0-1.52	0.0	4.0	26.5	69.5	Silt Loam
78	Andh_S_2		3.05-4.6	1.6	10.9	11.7	75.8	Silt Loam
79	Andh_S_3		6.1-7.6	2.2	4.3	24.1	69.4	Silt Loam
80	Andh_S_4		9.14-10.7	1.7	10.7	15.7	71.9	Poorly Gravelled Silt Loam
81	Andh_S_5		12.2-13.7	2.3	19.2	11.2	67.2	Silt
82	Andh_S_6		15.2-16.7	0.9	0.9	36.7	61.5	Silt
83	Andh_S_7		18.3-19.8	4.8	8.4	19.8	67.0	Poorly Gravelled Silt Loam
84	Andh_S_8		21.3-22.9	3.5	4.2	27.0	65.3	Poorly Gravelled Silt Loam
85	Andh_S_9		22.9-24.4	0.9	4.4	40.0	54.6	Silt Loam

5.5.2 XRD and XRF analysis

To study the chemical and mineralogical properties of the sediment samples-Xray fluorescence spectroscopy (XRF) and X-ray powder diffraction (XRD) and Scanning electron microscopic (FE-SEM) analyses were carried out for the selected samples. The XRD patterns of the bulk sediment of the Simaria, Baligaon and Anhari sediment are presented in Fig. 5.23. In all the analysed sediment samples, some characterized peaks were observed which indicates the type of minerals present in the soil samples (Table 5.9). Mostly, all the soil samples have a sharp peak at 8.84 and 12.34 Å indicates the presence of clay minerals i.e. illite and kaolinite minerals respectively. The peaks at 17.70 Å, 26.94 Å and 26.74 Å also indicates mica (muscovite) and quartz as prominent minerals respectively. Others significant peaks at 20.81, 50.11 along with 59.99 Å shows the presence of quartz. The reflections of 27.92 and 29.13 Å were used for identification of

Plagioclase-feldspar and calcite, respectively (Fig. 5.23). From XRD study of the sediment samples, it was found that quartz, clay and feldspar are the major minerals for most of the samples, whereas goethite and dolomite were present rarely in few sample only as minor minerals. Some minor peaks were observed indicating arsenic bearing minerals such as the presence of Iron arsenate ($Fe_2As_4O_{12}$) which may be observed at the peak intensity of the 23.99 Å reflections in Simaria sediment of arsenic affected area.

Table 5.9: List of common mineral assemblage in the sediment samples of Gangaalluvial plain at various locations in the study area.

Site Name	Ms	I	Gp	Kln	Gt	Qz	KF	Ab	Cal	($Fe_2As_4O_{12}$)
Simaria-A	√	√	√	√	√	√	√	√	√	√
Andhari	√	√	√	√	√	√	√	√	√	
Mauzampur	√	√	√	√	√	√	√	√	√	
Ishwerpura	√	√	√	√	√	√	√	√	√	
Simaria-B	√	√	√	√	√	√	√	√	√	√
Suhiya	√	√	√	√	√	√	√	√	√	
Sirsiyan	√	√	√	√	√	√	√	√	√	

Note: Ms: Muscovite, I: Illite, Gp: Gypsum, Kln: Kaolinite, Gt:Garnet, Qz: Quartz, KF; Potash feldspar, Ab:Albite, Cal: Calcite, FeAs: Iron arsenate.

Figure 5.24 shows X-Ray differactogram of heavy minerals which were separated from dominant lighter minerals (i.e. quartz, plagioclase, clay minerals) in the bulk sample using bromoform. Various peaks of various arsenics bearing minerals (i.e. Cesium arsenate, Dervillite, and Laumonite etc.) were identified using Expert Highscore software. Also, the sample was analysed using FESEM and SEM-EDX micrographshowing the elemental composition (wt%) of the various element present in sediment (Fig. 5.24 b).

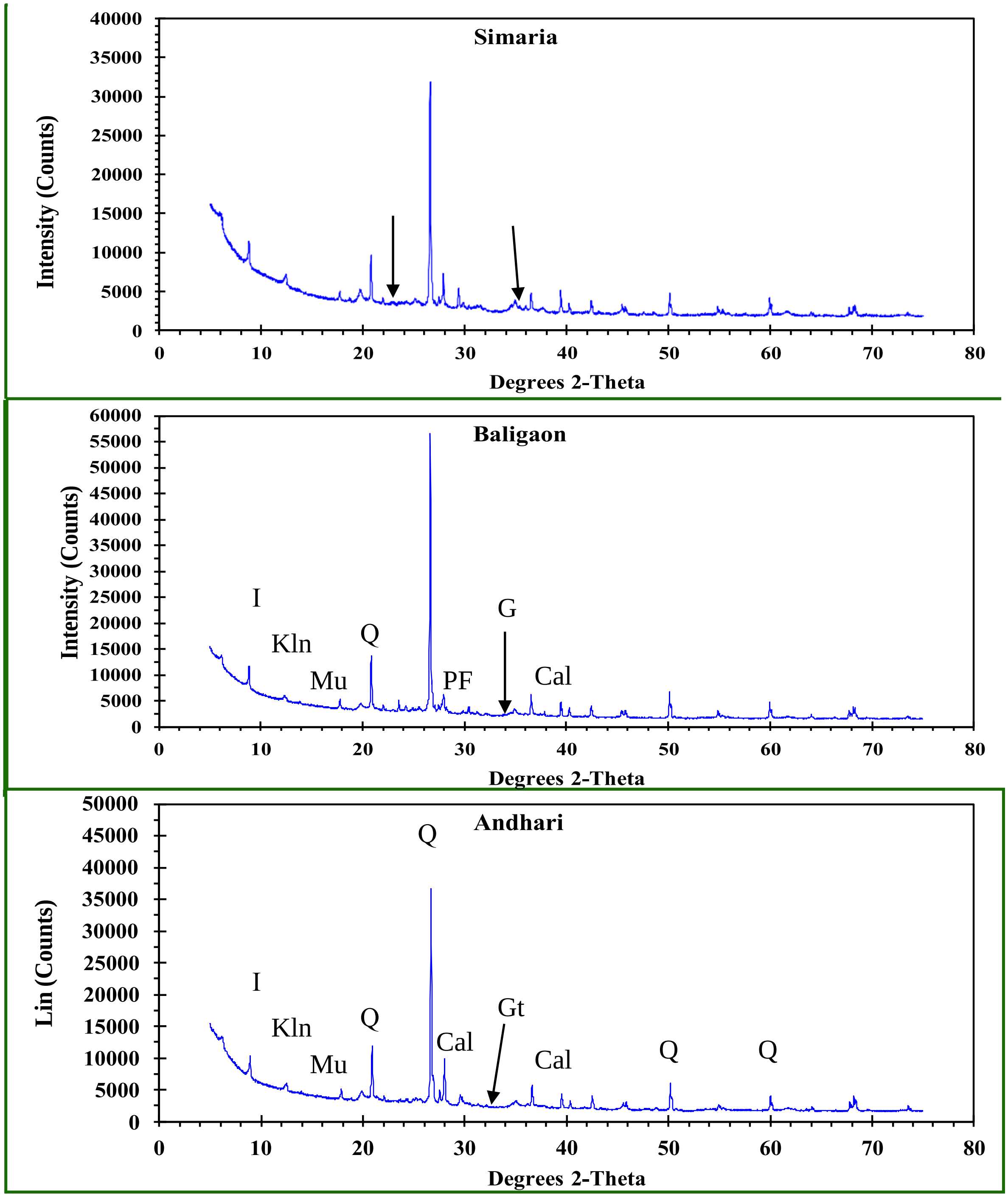


Figure 5.23: XRD pattern showing common mineral assemblage in the bulk sediment sample (Semariya) of Ganga alluvial plain at various locations in the study area.

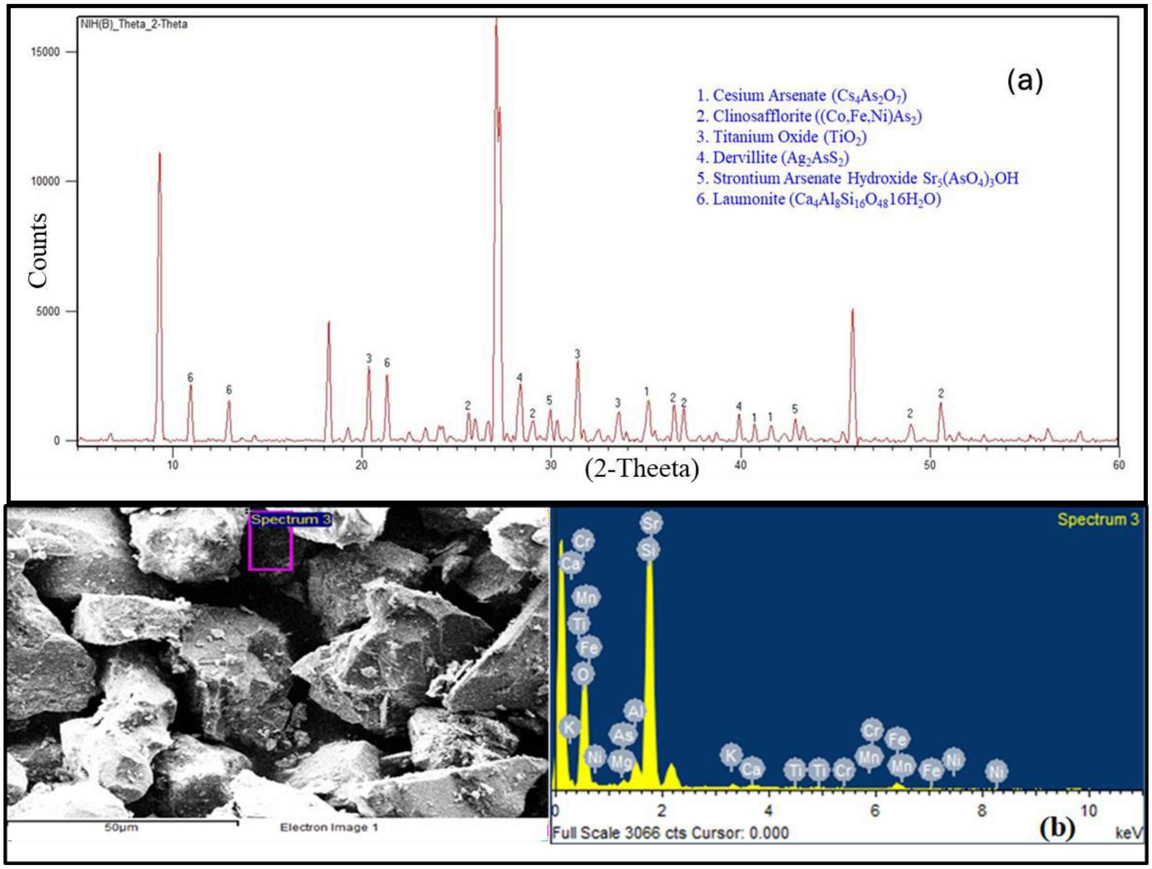


Figure 5.24: (a) XRD pattern showing common arsenic bearing minerals assemblage in the heavy mineral separated fraction sediment samples of Ganga alluvial plain at Simaria Ojha Patti (b) SEM-EDX showing elemental composition (wt%) of the various element present in sediment.

XRF Analysis:

Chemical analysis of sediment samples provides valuable information about potentially harmful trace elements such as heavy metals. On the other hand, the major-element and ion-chemistry analyses provide estimates of mineral components. The XRF analysis of sediment samples for the major oxides are presented in Tables 5.10. In general, the analysis reveals that all samples contain major amounts of SiO_2 as well as substantial Al_2O_3 concentrations. More specifically, major elements of all the sediment samples indicate presence of a predominant SiO_2 mass component (37.4% - 50.0%) with significant Al_2O_3 (4.0% - 16.2%), Fe_2O_3 (1.7% -10.0%), MnO (0.1% - 6.37%) and CaO (0.8 - 5.2 %) contributions; a few percent of K_2O (1.7% - 3.3%), MgO (0.2 - 1.8 %), P_2O_5(0.1% - 0.9%) and TiO_2 (0.3% - 1.0%), as well as trace amounts (<1%) of SO_3, Cr_2O_3, NaO, ZnO, CuO, BaO, SrO and NiO. The average relative abundance of major oxidesand trace metals for three different locations are shown in Fig. 5.25 and depthwise variation is shown in Fig. 5.26.

Table 5.10. XRF results of Anadhi, Simariya, Baligaon and Sirsiya sediment samples

Chemical Compositions of sediment samples (Bhojpur)																		
		Major oxide										Trace metals						
Sample ID	Depth	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	MnO	TiO_2	S	Cr	Ni	Cu	Zn	Ba	Sr
	(ft)	wt%										mg/Kg						
Andh_1	0-5	50.0	10.9	5.5	1.2	0.8	0.2	2.6	0.8	0.9	1.0	119	290	68	105	77	515	100
Andh_2	10-15	37.4	12.1	8.3	3.3	1.2	0.2	1.9	0.5	0.1	0.9	123	406	101	131	120	467	126
Andh_3	20-25	38.7	10.2	6.4	5.0	1.5	0.2	2.2	0.1	0.1	0.7	125	283	90	99	96	493	157
Andh_4	30-35	40.5	10.3	6.2	3.1	1.5	0.2	2.1	0.1	0.6	0.7	145	295	83	98	100	425	443
Andh_5	40-45	39.6	12.1	7.4	2.1	1.2	0.2	2.3	1.0	0.8	0.8	95	257	89	112	128	488	127
Andh_6	50-55	40.0	9.6	5.9	1.5	0.9	0.3	2.2	0.8	0.9	0.8	0	313	69	93	84	518	356
Andh_7	60-65	41.7	10.8	6.1	1.0	1.1	0.2	2.3	0.7	6.4	0.7	0	287	79	104	96	432	255
Andh_8	70-75	40.1	9.6	6.1	1.7	0.9	0.2	2.2	0.8	0.8	0.8	131	307	64	99	111	471	321
Andh_9	75-80	37.8	9.8	6.1	2.4	1.0	0.2	2.3	0.9	1.0	0.8	115	466	72	97	96	557	365
Sim_A1	0-5	43.6	16.2	10.0	5.2	1.8	0.2	3.3	0.1	0.2	1.0	241	194	124	158	364	646	146
Sim_A2	10-15	39.1	12.3	9.4	3.5	1.6	0.2	2.4	0.1	0.2	0.8	219	283	106	129	210	546	118
Sim_A3	20-25	39.7	11.9	8.6	3.9	1.6	0.2	2.3	0.1	0.1	0.8	219	213	108	146	178	530	135
Sim_A4	30-35	38.5	12.2	9.1	3.5	1.6	0.2	2.3	0.9	0.1	0.9	218	248	112	145	159	626	133
Sim_A5	40-45	45.2	5.9	3.1	3.4	0.8	0.4	1.9	0.7	0.6	0.3	121	216	53	73	51	0	255
Sim_A6	50-55	41.6	5.8	3.8	4.6	0.9	0.4	1.7	0.1	0.1	0.5	89	315	42	70	55	0	266
Sim_A7	60-65	42.1	5.8	3.1	4.5	0.7	0.4	1.9	0.1	0.8	0.4	96	324	43	77	48	0	278
Bali_S1	0-5	42.5	11.4	6.7	0.8	0.8	0.2	2.2	0.1	0.1	0.9	116	351	87	109	108	613	91
Bali_S2	10-15	42.6	11.3	7.0	0.9	1.0	0.3	2.1	0.2	0.8	0.9	123	367	97	115	118	470	113
Bali_S3	20-25	43.8	6.5	3.8	1.4	0.5	0.3	2.2	0.9	0.6	0.6	182	439	52	81	65	530	289
Bali_S4	30-35	48.8	9.4	4.4	1.3	0.7	0.3	2.8	0.0	0.9	0.8	283	638	61	101	68	0	91
Bali_S5	40-45	42.7	4.5	2.3	0.8	0.3	0.2	2.2	0.0	0.5	0.4	0	407	43	72	31	0	261
Bali_S6	50-55	41.4	8.5	5.4	1.1	0.7	0.3	2.3	0.0	0.8	0.8	268	0	66	101	89	0	274
Bali_S7	60-65	43.0	10.4	6.3	1.0	0.8	0.3	2.3	0.0	0.8	0.9	277	621	74	109	94	0	249
Bali_S8	70-75	39.8	8.1	4.8	1.0	0.6	0.3	2.2	0.0	1.0	0.8	0	525	62	90	75	0	275
Bali_S9	75-80	39.6	4.0	1.7	0.8	0.2	0.2	2.2	0.0	0.3	0.3	0	653	0	64	0	0	308
Sirs_1	0-5	39.4	9.2	5.8	3.9	1.2	0.3	2.2	0.0	0.9	0.7	0	380	79	109	88	0	353
Sirs_2	10-15	37.5	10.6	7.3	4.0	1.5	0.3	2.5	0.0	0.1	0.7	324	295	96	119	108	0	135
Sirs_3	20-25	40.7	10.7	8.3	1.7	1.1	0.2	2.0	0.0	0.1	1.0	0	419	96	144	108	0	115
Min		37.4	4.0	1.7	0.8	0.2	0.2	1.7	0.0	0.1	0.3	0.0	0.1	0.0	63.9	0.0	0.0	90.5
Max		50.0	16.2	10.0	5.2	1.8	0.4	3.3	1.0	6.4	1.0	324.4	652.7	124.2	158.2	363.8	646.0	443.3
Mean		41.3	9.6	6.0	2.4	1.0	0.3	2.3	0.3	0.7	0.7	129.6	349.7	75.6	105.4	104.6	297.4	219.1
Std		3.0	2.7	2.1	1.4	0.4	0.1	0.3	0.4	1.1	0.2	97.1	139.2	26.0	24.1	65.0	262.0	99.3

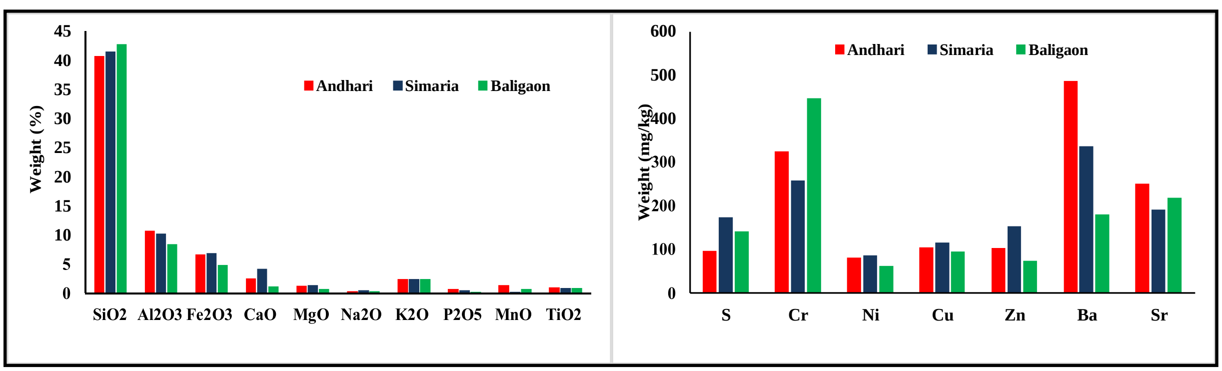


Figure 5.25: Average relative abundance of major oxide and trace elements in thesediment samples at various location of the study area.

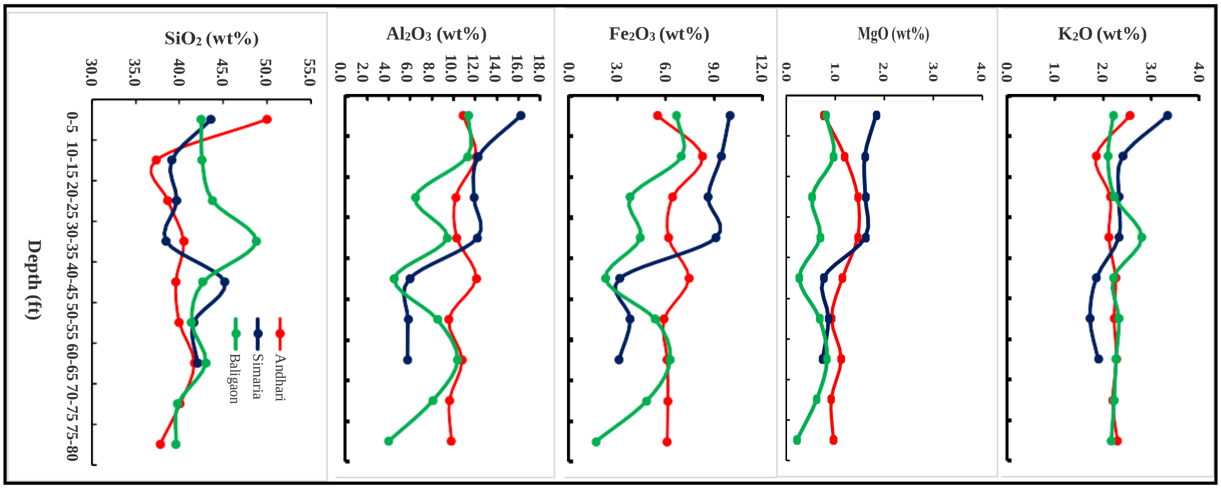
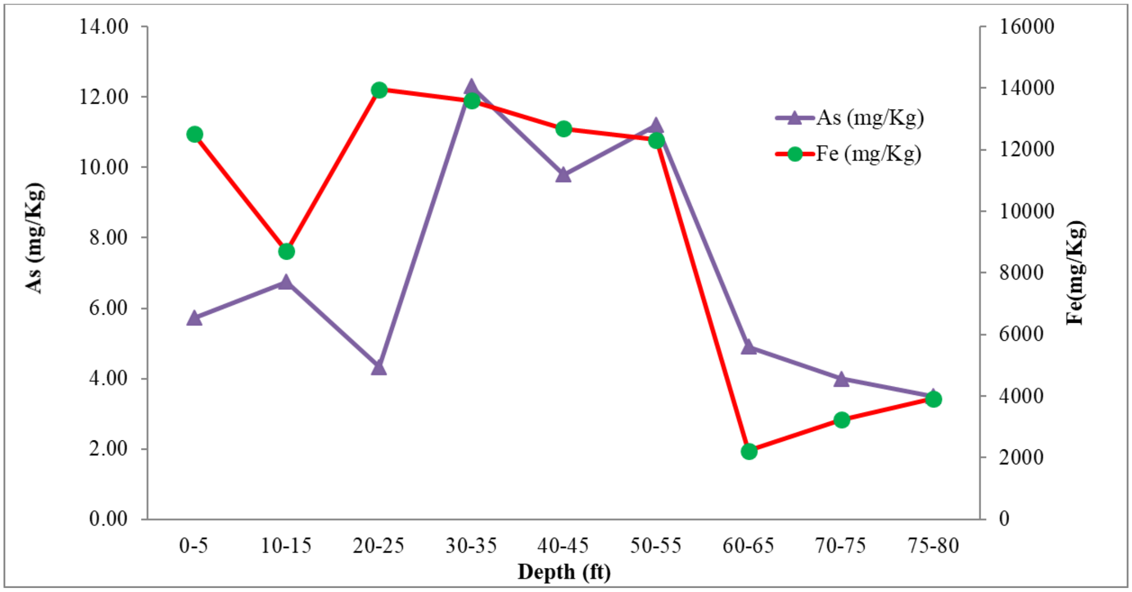


Figure 5.26: Vertical distribution of major oxides in sediments of the study area (Andhari, Simaria and Baligaon)

The arsenic concentration in the sediment samples was determined by ICP-OES and As varies from 1 mg/Kg 19 mg/Kg. Sediment samples was also analysed for organic matter concentrations in the selected samples. The depth-wise variation of organic matter with arsenic was studied. Figure 5.27 shows that As and Fe was found to more concentrated in the depth range of 9.14-15.24 m and organic matter was found to be less in this depth of Simariya samples. The Fe is showing similar trend as As is high in the depth range of 9.14-15.24 m. The lesser concentration of organics and elevated concentration of As supports the hypothesis that arsenic may be mobilizing due to microbial dissolution of iron oxy-hydrooxide.



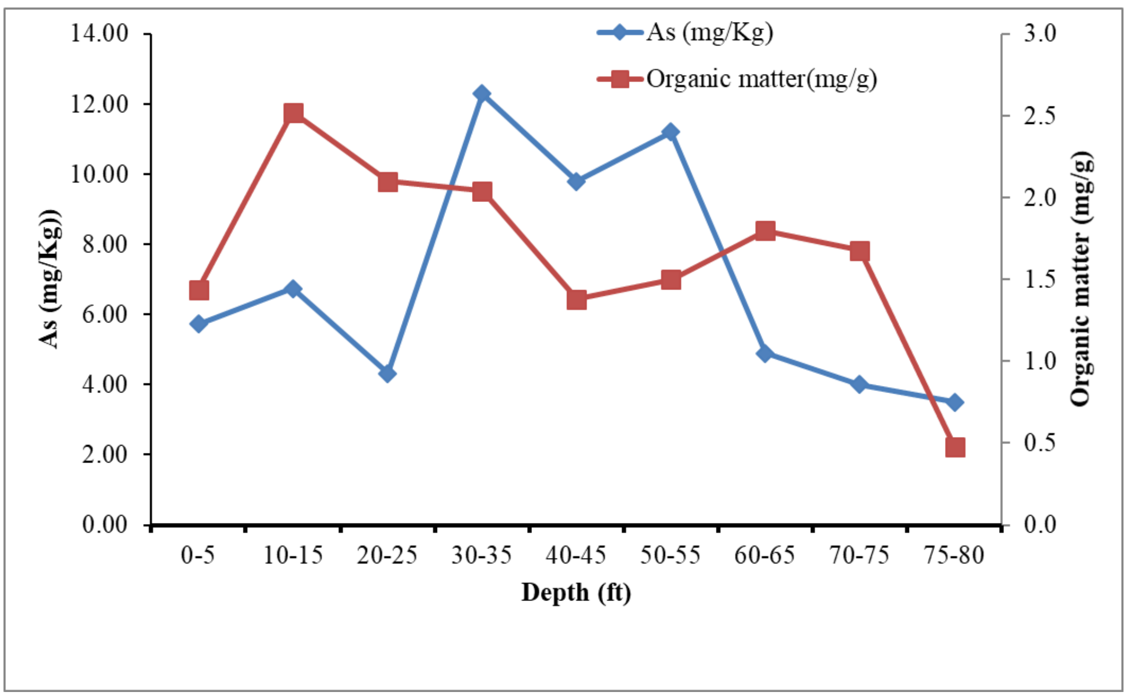


Figure 5.27: Depth wise variation of As, Fe & organic matter in sediment samples of Mauzampur village.

5.6: Batch and Column Experiment

The highest average arsenic concentration (19 mg/Kg) was found in the soil of Semriya village of the study area. Fig. 5.28 demonstrates the 8 days leaching results of batch experiment which was performed with 3 gm sample (simariya village) with 30 ml distill water at room temperature. It was observed that the maximum arsenic leaching (52 µg/Kg) was found on 1st day followed by 2nd (34.6 µg/Kg) and 3rd day (38 µg/Kg) and after that leaching rate was found to be constant i.e. approx. 12 µg/Kg. The Figure 5.28 b shows that maximum arsenic leaching happened at pH 8 which is consistent with the results of previous studies (Hwang et al., 2019). The increase in leaching time (3-8 days) do not significantly changes the leaching rate. After completion of batch experiment, column experiment was started with a packing of contaminated soil in a column with flow rate of 2ml/min and the constant leaching rate of arsenic from sediment has been found to be 4 ppb/day (Fig. 5.29).

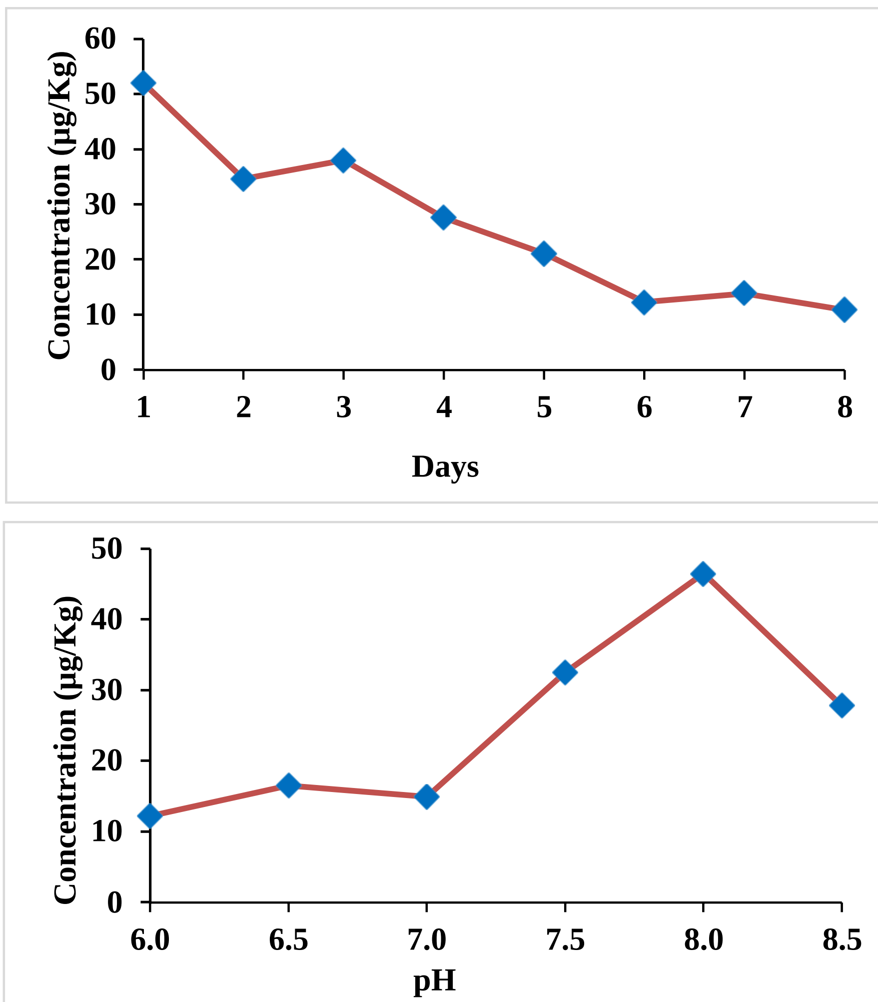


Figure 5.28: (a) Variation of arsenic concentration during batch-leaching test with (a) variable days and constant pH of 7.25 (b) variable pH (6-8.5)

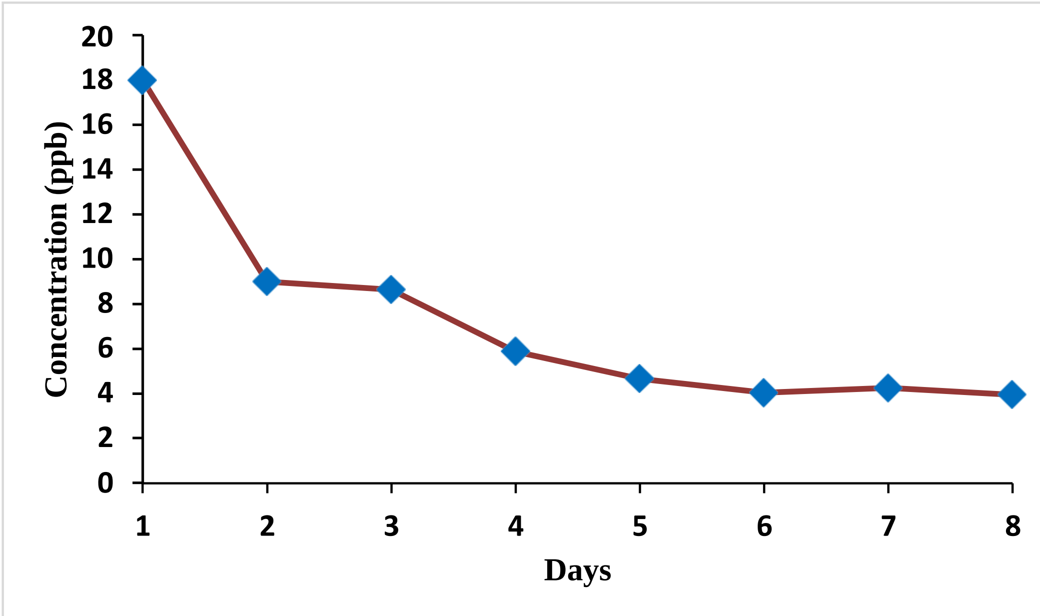


Figure: 5.29: Variation of arsenic during column experiment

6.0. CONCLUSIONS

The deterioration of ground water quality due to geogenic and anthropogenic activities causes a concern for policy makers. Ground water contamination with arsenic is one of the major threats to human health. In India, high concentration of arsenic beyond permissible limit of 0.05 mg/L in ground water has been reported from 86 districts of 10 States. The ground water of central Gangetic plain has been reportedto be severely contaminated with arsenic. Presently, a detailed investigation has been carried out for the Bhojpur district, Bihar (located in central Ganga basin) to study thedistribution, occurrence and mobilization of arsenic. The conclusions drawn based on the extensive lab and field work, analyses and data interpretation are as follows:

- pH in the study area are alkaline in nature and most of the samples fall under acceptable limit of the drinking water standards as prescribed by BIS (2012). EC value shows that groundwater is fresh in nature and generally suitable for drinking and irrigation purpose.
- Hydro-geochemical facies of the water is 'Ca^{2+}-Mg^{2+}-HCO_3^- type in the study area. The cation chemistry of groundwater showing elemental abundance follows the order $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ and abundance of anion follows the order of $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^- > F^-$.
- The geochemical analyses suggest that rock-water interaction is controlling the geochemistry, and chemical constituent of the groundwater is mainly controlled by carbonate weathering with limited contribution from silicate weathering.
- The dissolution/weathering of carbonate rock acts as a major contributor for Ca^{2+}, Mg^{2+}, and HCO_3^-, however, alumino-silicates minerals are the major contributor for Na^+, K^+, and SiO_2 in the study area.
- The trace metals result show that all the parameters are well within the permissible limit of drinking water except As, Fe and Mn in the younger alluvium of Ganga flood plain area of the study area.
- The arsenic in groundwater samples (covering entire district) ranges between ND - 206 ppb during post-monsoon season. However, the arsenic concentration ranges

from ND-337 ppb with average value of 78 ppb in arsenic in pre-monsoon season and samples were collected from arsenic contaminated area.

- It is observed that high arsenic concentrations have been found in the vicinity of Ganga flood plain (newer alluvium in northern and N-E part of study area) only, and it was absent in the groundwater of the areas in proximity to Son river the southern side of the study area.
- The vertical variation of As reveals that elevated arsenic concentration was encountered generally in shallower hand pump (upto 60 m bgl) and a rapid decrease in As conc. was observed beyond 60 m (bgl) depth.
- The groundwater level is generally not declining in recent years in the study area and arsenic concentration do not have any correlation with groundwater levels.
- The relationship of As with other water quality parameters were also studied and it was observed that strong positive correlation of arsenic with ORP and iron exist which may be indicating the process of arsenic mobilization is through reduction of iron oxide adsorbed with arsenic.
- Plots of analytical data on Wilcox (1955) diagram relating electrical conductivity (EC) to sodium percent (Na %) shows that all of groundwater samples of the study area are falling in excellent to permissible quality category for irrigation water. The SAR in the study area ranged from 0.28 - 3.5 meq/L which reveals that all the samples fall in excellent category for irrigation purposes.
- The isotopic analysis reveals the distinct isotopic signature of river Ganga, Son and groundwater samples. The Son river ($\delta^{18}O$ value -3.17‰) is highly enriched in isotopic signatures as compared to Ganga ($\delta^{18}O$ value -5.78‰). The isotopic result implies that Son is recharging groundwater, however, groundwater is contributing to the river Ganga.
- The isotopic signature reveals fast vertical recharge in younger alluvium located in proximity to river Ganga. Overall, it is evident that organic matter in the groundwater due to recharge from agricultural fields or domestic wastewater, mightreach to the aquifer during recharge processes which enhances the mobilization of arsenic through microbial dissolution.

- Tube wells/hand pumps with high nitrate concentration was found to contain low arsenic reaffirms the microbial dissolution of minerals playing a major role in the mobilization of As.
- Lithological profile largely represents a sandy channel-fill deposits with clayey silty over bank deposit at the top indicting a fluvial environment of deposition. Based on textural classification of soil samples, the soil/sediment of the study area are mainly Silty type.
- The mineralogical properties of sediment were studied using XRD and XRF technique. It is observed that quartz, clay and feldspar are the major minerals for most of the samples, whereas goethite and dolomite were present scarcely in few sample. The arsenic bearing minerals such as iron arsenate ($Fe_2As_4O_{12}$) present in the bulk sample in trace amount in the samples where elevated concentration of arsenic has been found.
- In general, the XRF analysis reveals that all the samples contain major amounts of SiO_2 as well as the substantial Al_2O_3 concentrations. The average relative abundance of major oxides are classified as:

$$SiO_2 > Al_2O_3 > Fe_2O_3 >> CaO > MgO > K_2O > MnO > TiO_2 > Na_2O > P_2O_5$$

- Sediment (Mauzampur village) chemistry results indicate that As (13 mg/Kg) and Fe (12000 mg/Kg) was found more concentrated in the depth range of 9.14-10.66 m and the organic matter is less in this depth, which support the hypothesis of arsenic release due to microbial dissolution of iron oxides. Similar observations are noticedfor other locations also.
- The batch and column experiment results reveal that maximum arsenic leaching happens at pH 8. It was observed that the maximum arsenic leaching (52 µg/Kg) was found on 1st day followed by 2nd day (34.6 µg/Kg) and 3rd day (38 µg/Kg) and after that leaching rate was found to be constant i.e. 12 µg/Kg.

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APPENDIX-A Project summary

Table A.1: Summary

Project objectives		
Objectives as per project document	Revised objective	Reasons for revision
• Determination of the spatio-temporal variation of arsenic along with other water quality parameters in groundwater • Delineation of arsenic safe zone for drinking water supply • Evaluation of the controls of hydro-geology on arsenic contamination through monitoring of contaminated aquifer and sediment characterization. • Identification of the mechanism of release and transport of arsenic in GW through a column experiment	NA	NA

***Manpower* deployed (against sanctioned manpower)**			
Sanctioned: 03		Deployed: 03	
Designation	Person months	Designation	Person months
1 RA 1 PA-I 1PA	42 months	1 RA 1 PA-I 1PA	42 months

Infrastructure/ equipment		
Planned (as per project proposal)	Developed/ procured	Reasons for deviation
Purchase of Multi-parameter analyzer, Weighing balance, Analytical freezer and experimental column set-up	Purchased all	NA
Field work		
Planned (as per project proposal)	Completed	Reasons for deviation
Pre and Post monsson samplings, drilling etc.	Completed	NA

Workshop/ Capacity building/ technology transfer			
Planned (as per project proposal)	Organized	Reasons for deviation	
Not planned	-	-	
Study area			
Planned	Extended		
Bhojpur District, Bihar	NA		
New data generated in the project			
Planned (as per project proposal)	Achievement	Reasons for deviation	
Water quality data with specific reference to arsenic	Generated the WQ data	NA	
Envisaged contribution of the project			
Planned (as per project proposal)	Contribution made	Reasons for deviation	
WQ data generation, delineation of arsenic safezone aquifer, Understanding occurrence and mobilization of arsenic	Completed as planned	NA	
How research outcome benefited the end user department and society			
Planned (as per project proposal)	Benefit derived	Reasons for deviation	
New database related to arsenic contamination in the study area, depth of aquifer identified as contaminated zone, causes of arsenic occurrence and its mobilization which may help in adopting mitigation strategy	Achieved as planned with future scope to work further	NA	
End-of-project deliverables			
Planned (as per project proposal)	Achieved	Reasons for deviation	
Reports and Research Papers	Yes	NA	
Outsourcing (>1 lakh)/ consultancy (All)			
Consultant (name and qualifications), organization / outsource agency	Work assigned	Estimated cost Rs	Actual cost Rs
NA			

Financial achievement					
S No	Head	Approved budget	Approved revised budget	Final expenditure	Reasons for deviation
1	Remuneration/Emoluments for Manpower etc.	27,43,200	39,76,947	39,76,947	Increased due to revised salary of project staffs. However total project cost was kept same
2	Travelling Expenditure	8,80,000	10,44,138	10,44,138	Due to increased field visits
3	Infrastructure/Equipment	21,30,000	-	13,31,453	Manual drilling was done instead of proposed core drilling
4	Experimental Charges/Field work/Consumables	9,75,000	-	5,10,780	Overestimated the charges
5	Capacity building/Technology transfer	-	-	-	-
6	Contingency	2,70,000	-	1,28,958	
7	Outsourcing/ consultancy	-	-	-	-
	Total	70,00,000	-	69,92,276	The project was completed within approved budget

Table A.2: Quantitative outcome

i. Research papers published/ submitted		
S No	Research paper (National/ International Journal/ conferences/ symposium/ workshop/ seminar)	Impact factor for Journal
1.	**Kumar, S.,** Kumar, V., Saini, R. K., Pant, N., Singh, R., Singh, A., ... & Kumar, M. (2021). Floodplains landforms, clay deposition and irrigation return flow govern arsenic occurrence, prevalence and mobilization: A geochemical and isotopic study of the mid-Gangetic floodplains. *Environmental Research*, 201, 111516	6.49

2.	**Kumar, S.,** Kumar, M., Chandola, V.K., Kumar, V., Saini, R.K., Pant, N., Kumari, N., Srivastava, A., & Chaudhary, A (2021). Groundwater Quality Issues and Challenges for Drinking and Irrigation Uses in Central Ganga Basin Dominated with Rice-Wheat Cropping System. *Water*, 13(17):2344	3.10
3.	**Kumar**, S., Kumar, V., Saini, R.K., Raju, M., Singh, A., Singh, R., Singh, S., Mittal, S., Choudhary, A. (2019). Arsenic Contamination in Groundwater of Bhojpur District, Bihar, India. HYDRO-2019, organized by Osmania University and the Indian Society for Hydraulics during 18-20 Dec., 2019 at Hyderabad	Conference presentation
4.	**Kumar, S.,** Kumar, V., Singh, A., Raju, M., Tyagi, P., Saini, R.K. (2019). Arsenic Contamination of Groundwater in Central Ganga Basin and Possible Remediation Methods: A Review. IGWC-2019, organized by IIT Roorkee during 21-24 Oct., 2019 at Roorkee.	Conference presentation

Reports/Monographs/Internal publications brought out

S. No.	Reports/Monographs/Internal publications
1.	1 Report which is being submitted to NHP

ii. New techniques/models/ software/ knowledge developed, if any

iii. Web site/ application developed

Name	Web address	Server location	Launch date	Details of information available
NA				

iv. Patents filed/awarded, if any

Workshop/ conferences/ seminars/capacity building programmes organised

S. No.	Topic	Dates, duration, No. of participants	Report published (Y/N)
NA			

v. Stake holders feedback and action taken on constructive feed back

S No.	Feedback received	Action taken
Had meetings regarding the project with IA.		

vi. Field observations obtained, thematic maps generated (water quality and salinity, isotope, soil moisture, stage and discharge, sediment, water level, river cross sections, geophysical/ resistivity survey, hydrogeological investigations etc.)

S No	Parameter, frequency, period, groundwater/ river/ tank/ hand pump/ spring/ sea-water	Number (planned)	Numbers (measured)
1.	WQ parameters (pH, EC,	4 times	3 times

	TDS, Na, K, Ca, Mg, HCO_3, SO_4, NO_3, Cl and trace metals (As, Cr, Cu, Co, Cd, Ni, Mn, Fe and Zn). Isotopic data (Stable isotopes ($\delta^{18}O$, $\delta^{2}H$)	1 time	1 time

vii. Field installations (piezometers, river stage/ discharge, soil moisture etc.)

S. No	Name, make/ model	Unit price, total price, quantity	Date of installation	% utilization	Remarks regarding maintenance/ breakdown
1.	Piezometers (shallow depth 80 ft, manual drilling)	Total price Rs. 2.5 Lakh 7 Nos. piezometer	Nov. 2019	100%	NA

viii. Equipment/ software purchased

a. Equipment purchased

S. No	Name, make/ model	Unit price, total price, quantity	Date of installation	% utilization	Remarks regarding maintenance/ breakdown
1.	Hach, Multi-parameter analyzer (HQ 40d)	Rs. 2.49 Lakh 1 No.	June,2020	100	All the instruments have been used in the PDS
2.	Weighing balance	Rs. 2.24 lakh 1 No.	Oct. 2019	100	
3.	Lab Refrigerator	Rs. 68 thousand 1 No.	June, 2020	100	
4.	Column set-up	Rs. 2.28 lakh 1 No.	Dec. 2019	100	
5.	Data Logger	Rs. 5.49 laks 6 Nos.	July, 2020	100	

b. Software purchased

S. No	Name, version, license	Unit price, total price, quantity	Date of installation	% utilization	Remarks regarding maintenance/ breakdown
NA					
ix. Plans for utilizing the equipment facilities in future					
S. No.	Installation/ equipment		Planned future use		
All purchased minor equipment are being used in another study. It is also planned to follow-up this research work in the same area by getting funding from some agencies					
x. Data dissemination policy for data generated in the project					
xi. Number of post-graduate/doctoral candidates completed their courses (Please give a list of such candidates) 1. Manish Kumar, "Geo-chemical characteristic of arsenic affected aquifer of Bhojpur district, Bihar, India". **M.Tech**, Soil and Water Conservation Engg., Institute of Agricultural Science, Banaras Hindu University (BHU), Varanasi (2018-19). **2.** Ameesha Raj, "Groundwater Quality Assessment of Bhojpur District, Bihar, India". **M.Sc**, Earth Science, School of Ocean Studies and Technology, Kerala University of Fisheries and Ocean Studies, Kochi (2019-2020)					
xii. Foreign deputation/visit of PI/Co-PIs/students, if any					

A.3 Activity chart

Include activity chart/ modified activity chart, reasons for modification of activity chart.

Sr. no	Activity	Status
1	**Conceptual Model Construction**	Completed
2	**Drilling of Borehole**	Completed
3	**Water chemistry sampling & analysis**	Completed
4	**Development of column experiment set up and analysis**	Completed
5	**Sediment Characterization**	Completed
6	**Causes of arsenic occurrence and its mobilization in groundwater**	Completed
7	**Preparation and submission of reports & publications**	Completed