Prospects of Arsenic Mitigation in Asia : Arsenic Mitigation of Groundwater at Punjab state in Pakistan

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Arsenic Mitigation of Groundwater at Punjab state in Pakistan

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Abstract

The arsenic mitigations have been performed in the basins of the Ganges River, the Yellow River and the Mekong River by many agencies, but not so enough in the basins of the Irrawaddy River and the Indus River. We had a chance to survey the arsenic contamination of groundwater at Punjab division in the Indus basin, Pakistan. Although the values of Oxidation-reduction Potential, ORP, are negative and almost same as in the Ganges basins, the concentration of ferrous iron is very low. The groundwater in the Ganges basins are under the reducing condition and the concentration of ferrous iron is high. The arsenic removal unit had been developed by using the iron function of co-precipitating with arsenic, and many units have been operated in the Ganges basins. The groundwater in the Indus basins seems in general to be under the oxidizing conditions, partially under the reducing condition. This may be caused from the evaporation in semi-arid climate, the recharge from canal leakage water, return water from irrigation, and anthropogenic pollutants such as fertilizers and wastes from industry & household. We designed an arsenic removal unit, increasing the concentration of ferrous iron by putting iron metal bars in the unit.

Keywords: Arsenic, Groundwater, Indus, arsenic removal, water quality

1. INTRODUCTION

Arsenic contamination of groundwater currently occurs in various regions across the world, such as Asia and North & South America (H. Yokota 2006). Arsenic contamination of groundwater, in Asia, is seen in the basins of the great rivers, originating in the Himalayan Mountains and the Tibetan Plateau, such as the Ganges River, the Indus River, the Mekong River, the Hor River, and the Yellow River [Yokota, H 2004], where people depend on groundwater for the drinking water.

A part of arsenic contaminated areas is shown in Fig.1. A thermally altered metamorphic zone in the Higher Himalaya, containing various types of minerals, is considered as the source of arsenic [R. B. Sah, et al., 2002].

Arsenic contaminations of groundwater in West Bengal, India (Foogri River basin), Inner Mongolia Autonomous Region, China (Yellow River basin) and Bangladesh (Meghna River basin) are known for long, in which the detections of the arsenic contamination are in 1982, 1989 and 1993, respectively. The investigations and countermeasures in those areas have been performed by University of Miyazaki and AAN (Asian Arsenic Network) as follows.

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The University of Miyazaki had elucidated the mechanism for arsenic contamination and developed the safe water devices in Bangladesh and Nepal together with AAN since 1997 [Yokota, H. *et al.*, 2006], and also has conducted activities for arsenic mitigation in UP (Uttar Pradesh State), India under a JICA technical cooperation project from 2008 until now in collaboration with AAN [Yasunori Yano, *et al.*, (2009, 2012)].
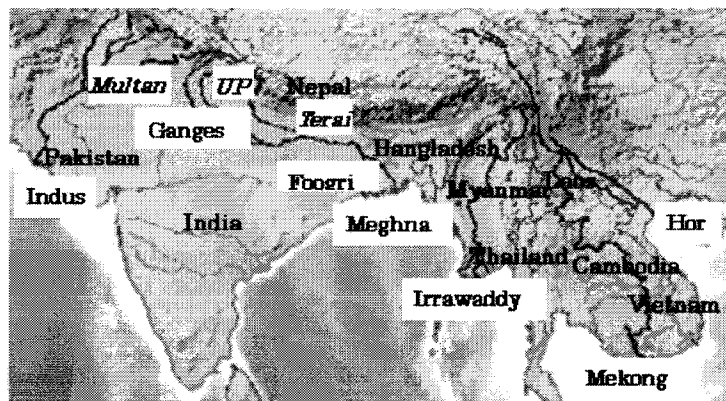

Fig.1 Arsenic contamination in Asian countries

In Bangladesh, AAN had surveyed the arsenic contamination from 1996 and implemented the Arsenic Mitigation Project twice these ten years from 1999 with the technical cooperation of JICA [JICA, *et al.*, (2004), Ministry of Local Government (Bangladesh), *et al.*,(2008)], and is now promoting a new JICA technical cooperation project for building a service model of local government for safe water supply. Also, AAN had implemented the arsenic mitigation in Inner Mongolia with RGAG (Research Group for Applied Geology) 1996 to 2004 [RGACGIM (2007)].

On the other hand, at Mekong River basins in Vietnam, Cambodia and Laos, arsenic contamination were first confirmed around 2000 and countermeasures just began under help such as UNICEF, GIST (Gwangju Institute of Science and Technology) [K. W. Kim, *et al.*, (2011), K. H. Cho, *et al.*,(2011)] and AAN & RGAG [AAN,*et al.*,(2012)].

The mitigations of arsenic contamination in the Ganges, Yellow and Mekong basins have been also implemented by each government in the basins and other international agencies, though no mentioned here. However, the mitigations in other basins, such as the Irrawaddy and the Indus, are not so implemented as in the basins of the Ganges.

The ground water in the Indus basin seems to be under the oxidizing condition [World Bank (2005)], though reducing conditions in the basins of Ganges, Mekong and Yellow. We had the chance to survey the arsenic contamination of groundwater in the basin of Indus and to design an arsenic

removal unit at Punjab division, Pakistan, during support activities for the sufferers by severe flood from the Indus in the summer 2010.

Some of new tube wells were contaminated with arsenic, which were installed by Japanese NGO, NICCO (Nippon International Cooperation for Community Development), which has supported the sufferers of villages for housing, drinking water and medicine at the villages about 80km western from Multan in Punjab division together with the local NGO, Safe Winds Organization, since September 2010.

The Fe^{2+} concentrations of groundwater at the villages were very low, which is to be needed in arsenic removal unit, though the value of ORP showed almost same as those in Bangladesh and India.

Here, the water quality characteristics of groundwater are discussed in comparison with those in other areas of Pakistan and in Ganges basins. Also, the design of arsenic removal unit is shown, which may be used, in future, at the arsenic contaminated groundwater area with little Fe^{2+} concentration in the world..

2. ARSENIC CONTAMINATION IN PAKISTAN

2.1 Arsenic contamination in Punjab and Shindh divisions

The groundwater in Pakistan is contaminated at the eastern (Punjab) and southern (Sindh) along the Indus and its tributaries. It was made clear by the survey of PCRWR (Pakistan Council of Research in Water Resources, Ministry of Science & Technology) under support of UNICEF in 2000~2005. The situations of arsenic-contaminated tube wells, obtained by the sample tests in all districts of Punjab (31,693 samples) & Sindh (67,556 samples), is shown in Table 1[M. A. Kahlown, *et al.*, (2003)].

Table 1 Arsenic contamination in Pakistan

Division	As<10ppb	10<As<50ppb	50ppb<As
Punjab	60%	31%	9%
Sindh	47%	36%	17%

The high arsenic concentration in Punjab, 250~400ppb, has been seen in the 6 districts along the Indus and its tributaries, and serious arsenic contamination over 1000 ppb has also been found in the 2 central districts in Sindh. And, it was mentioned that the arsenic concentration had no relation with the well depth, values of pH & EC and iron concentration.

2.2 Arsenic contamination in Multan suburb at the south-western Punjab

Nickson *et al.* showed the test results of 49 samples in the Muzaffargar district next to Multan district, which was one of the high arsenic-contaminated 6 districts mentioned above, as follows [R. T. Nickson, *et al.*, (2005)].

a) Shallow tube wells (42 wells, depth<30m)

Arsenic concentration in urban area was 0~270ppb, in which the arsenic enrichment was caused by reduction of hydrous ferric oxide through pollutant organics from unconfined sewage, etc. In addition, the possibility was indicated that the arsenic contamination was caused from the direct contaminations of industrial and agricultural chemicals.

Arsenic concentration in rural area was less than 25ppb. The low concentration happened from the strong sorption of arsenic to aquifer sediments in the groundwater under the oxidizing condition.

b) Deep tube wells (7 wells, depth>30m)

Deep wells were all installed only in the urban area and the arsenic concentration was 80~170ppb. The data would seem to suggest the reduction of hydrous ferric oxide by naturally-occurring organic matter. Arsenic concentrations seemed to increase with depth, suggesting that arsenic concentrations in older groundwater might be governed by different processes.

c) The reducing condition, which was seen partially, might be caused by microorganism activities, following the arsenic release from hydrous ferric oxide.

2.3 Arsenic contamination in area near Lahore at the eastern age of Punjab

A. Farooqi, *et al.*, reported the following arsenic and fluoride contaminations by testing 147 samples of tube wells, the depth of which were 27~30m (123 samples), 40~80m (14), 80~200m (8), in the area covering $1/5^{th}$ of Kasur and $1/6^{th}$ of Lahore districts [A.Farooqi, *et al.*, (2007)].

a) 91% of samples exceeded 10 ppb and maximum concentration was 2.4ppm for arsenic contamination, and 75% for 1.5ppm (WHO standard) & maximum value of 22.8ppm for fluoride contamination

b) Arsenic and fluoride contaminations occurred in the oxidizing and alkaline conditions (Eh=218~364mV, pH=7.2~8.7, Alkalinity as $HCO_3^- =1,281$ppm).

c) Arsenic was mostly in the form of As^{5+} and showed a positive correlation with pH and no relationship with Fe.

d) Highly alkaline and low Ca^{2+} and Mg^{2+} promoted high concentrations of arsenic and fluoride.

e) The source of arsenic contamination was air pollutants derived from kiln factories, with fertilizers being a possible secondary source.

Table 2   Comparison of water quality between Indus and Ganges basins (ppm except pH, Eh and EC)

	Pakistan			India	Bangladesh	Nepal	Inner Mongol
	Ghazi Ghaat	Multan	Rahore	Bahraich	Samta	Terrai plain	Hetao plain
pH	6.3~8.7	6.6~8.6	7.2~8.7	6.8~7.5	7.1~7.6	6.9~7.5	7.4~9.0
Eh	26~190 mV			70~160 mV	110~180 mV	70~170 mV	-230~198mV
			218~364 mV	260~420 mV		230~300 mV	277~347mV
EC		0.31~7.05 mS/cm	0.40~4.60 mS/cm	0.42~1.27 mS/cm	0.57~1.37 mS/cm	0.62~1.98 mS/cm	0.56~6.40 mS/cm
As	0~0.5	0~1.0	0~2.4	0.05~0.1 >0.1	0~1.2	0~0.9	0~0.65
Fe	0.01~2.0	0~2.7	0~2.8	0.05~1.5	1.2~10.5	2.0~13.0	0~11.4
HCO3		150~1500	150~1300		180~430	360~700	240~1090
NO3-N	0~3.6	0~53	0~46	0.02~0.6 >1.0	0~0.1	0~1.8	1~3.0
NH4-N	0~0.6	0~60		0~2.2	0.5~6.5	0~1.8	1~1.2
SO4	16~249	0~1320	24~960	0~45	0~8	0~300	2~470
PO4	0~0.2, 1.2	0~0.3, 26.4	0~3.3	0~2.6		0~0.9	0~1.8
Cl	0~168	10~1500	4~415	1~10 >25	0~58	4~500	70~1800
Na		10~1300	12~1060		10~100	10~35	40~1280
Ca	0~137	1~230	2~138		40~100	2~10	6~135
Mg	7~50	10~200	2~61		10~50	5~20	10~180
F	0~0.8		0.5~22.8		0~4.0	0.2~2.3	0.1~2.9

f) Major sources of fluoride and SO_4 seemed to be fertilizers.

2.4 Arsenic concentration and water quality at the villages in Ghazi Ghaat county, Muzaffargar districts

As the tube wells in the villages had been destroyed by the flood, NICCO installed new 300 tube wells in 2011. The depth of old destroyed tube wells was about 10m and NICCO's new one was about 30m, which supplied clean colored water, but 20% of tube wells showed arsenic contamination beyond 50ppb (34% for As>10ppb). Highest concentration value was 500ppb (2 tube wells).

The water quality for 80 tube wells out of the above-mentioned 300 tube wells is shown in the APPENDIX. It is compared with those in Multan suburb and Lahore suburb in Table 2 as follows.

a) The arsenic contamination, in 2012 for 80 samples, shows 25% for As>50ppb (200ppb: 5 samples, 400ppb: 1 sample), which was almost same as the arsenic affected levels, measured in 2011 for 300 samples mentioned above (refer to the APPENDIX).

b) The value of oxidize reduction potential, Eh, in the villages shows about 26~190mV and less oxidizing condition, compared with those in Lahore suburb (Eh=218~364mV).

c) The value of pH, 6.3~8.7, is almost same as Multan suburb (6.6~8.6) but less alkaline compared with Lahore suburb (7.2~8.7).

d) Iron concentration, needed for arsenic removal unit, is very low (0.01~2.0ppm). The unit is the AIRP/GSF (Arsenic Iron Removal Plant /Gravel Sand Filter), which had been developed by UOM in Bangladesh. Many GSFs have been installed in Bangladesh and India. The arsenic removal mechanism of GSF is the co-precipitation of iron with arsenic. The groundwater is almost under reducing condition in Bangladesh and India, where arsenic exists with high concentration of iron (Fe^{2+}).

The major values of iron 0.01~2.0ppm, mentioned above, belong to the range of 0.01~0.49ppm and high concentration is only for 4 samples (1.27, 1.41, 1.67, 2.0ppm). This situation is almost same as those of Multan and Lahore. It means the direct use of GSF is impossible, because the concentration ration of Fe/As should be larger than 15 as mentioned later for arsenic removal by Iron co-precipitation.

e) The concentrations of NO_3-N (0~3.6ppm), PO_4^{3-} (0~0.2ppm), SO_4^{-2} (16~249ppm), and NH_4^+ (0~0.6ppm) are in general low compared with those of Multan and Lahore. Accordingly, the anthropogenic activities on the ground surface may not influence to arsenic contamination of groundwater, which was discussed in the urban areas in Multan and Lahore.

f) The low concentration of Fe^{2+} was illustrated by Eh-pH-Iron diagram which shows the chemical form of iron in the water.

2.5 Comparison of water qualities in the Indus with the Ganges basins

The comparison is mentioned as follows from Table 2.

a) The iron concentration is very low compared with those in Bangladesh (and Inner Mongolia).

b) The value of Eh in Ghazi Ghaat is almost same as those in Samta and one group of Bahraich, where GSFs are working well under the high Fe concentration, satisfying the criterion of Fe/As>15 mentioned later. This is the biggest difference between the Indus and the Ganges basins.

c) The concentration of NH_4-N in Ghazi Ghaat is low compared with Ganges basins, which may express less reducing conditions.

d) The concentration of NO_3-N in the Indus basins, especially Multan and Lahore, is high compared with Ganges basins (and Inner Mongolia), which may express oxidizing g conditions.

3. DEVELOPMENT OF ARSENIC REMOVA UNIT IN PAKISTAN

3.1 Arsenic removal performance of AIRP/GSF in Bangladesh

GSF is composed gravel tanks and sand tank as shown in Fig.2. The sizes of gravel and sand tanks are about $0.7m^3$ and $1.4m^3$ (height of tank=1.0m), respectively. The arsenic removal mechanism is as follows [Hussainuzzaman, M., et al., (2006)].
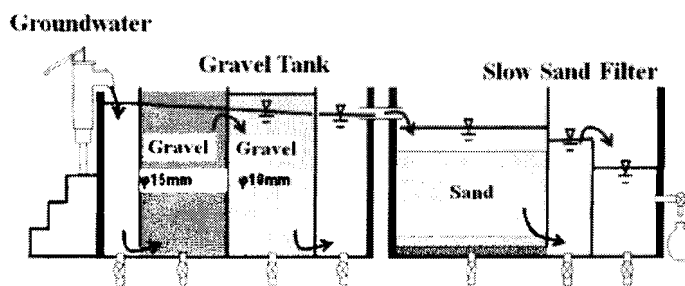

Fig.2 The structure of AIRP/GSF

a) The ferrous iron Fe^{2+} and arsenite As^{3-}, which are dissolved in the groundwater under the reduced condition,

are to be oxidized to the ferric iron Fe^{3+} and arsenic As^{5+} in the inlet through aeration. Fe^{3+} precipitates in the form of Fe $(OH)_3$ with arsenic in the gravel tanks.

b) The co-precipitated material of Fe^{3+} and As^{5+} is to be accumulated in the gravel voids of the gravel tanks.

c) The co-precipitated material (arsenic sludge) in the gravel voids is removed from the gravel tanks by periodical drainage.

Arsenic is removed with iron as mentioned above, and phosphate is competition to arsenic for iron co-precipitation. We made, therefore, such criterion as Fe/As>15 for 0<P<1.0ppm and Fe/As>30 for 1.0<P<3.0ppm. The performance of arsenic removal in Bangladesh is almost 80~98% shown in Fig.3
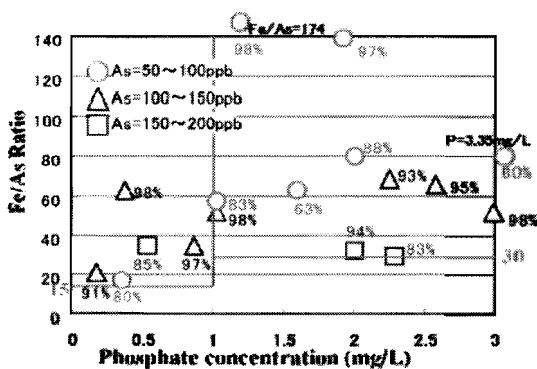

Fig.3 Arsenic removal performances of AIRP/GSF in Bangladesh

3.2 Laboratory tests of increasing Fe^{2+} concentration by using iron metal bar in Pakistan

As the Fe^{2+} concentrations of groundwater at the villages in Ghazi Ghaat county was very low, we made the following model tests at laboratory in NICCO office to increase the Fe^{2+} concentration in the inlet tank of GSF.

We put one iron metal bar (2cm×0.2cm×30cm) into a 1.5L bottle filled with tap water of As=0.3ppm in NICCO office. The tests were performed by the water research group of NICCO office headed by Yasir Abbas in the collaborative research with Prof. Hafiz Badaruddin Ahmed of Bahauddin Zakariya University Multan. Fig.4 shows the increase of Fe^{2+} concentration in the bottle water until out range of Fe^{2+} meter. The dotted line expresses the needed retention time to get Fe^{2+} concentration of 4.5ppm satisfying Fe/As=15 (phsophate concentrationis is less than 1.0ppm here). The retention time is estimated 2 hours.

Fig.5 shows the decrease of arsenic concentration in bottle water, which may be caused by iron co-precipitation with arsenic. The initial arsenic concentration of 0.3ppm in the bottle decreased to 0.05ppm after 7~8 hours.

3.3 Design of AIRP/GSF by using iron metal bar

a) Water flows in GSF and water demand in design

In GSF, water velocity in gravel tanks during pumping is about 2m/h, and the water from gravel tanks infiltrates into sand tank with velocity of about 11cm/h.

The followings are estimated in the design of GSF at the villages of Muzaffargar.

1) Water demand is 1200L/day (4L/person/day, 5persons /family, 60 families).

2) The water is pumped up mainly in the morning and evening with 600L for 3 hours, respectively.

As the flow rate in gravel tank is about 1400L/h, water flow in the design (200L/h) has no problems. In the sand tank, it takes 4 hours for the volume of 600L, coming from gravel tank, to infiltrate into sand tank and be stored in the 800L of supply tank.

b) Application of laboratory tests to GSF

We decided to put the same iron metal with height of 1m in the inlet tank of GSF. After the analogical analyses between the test results of Figs.4 & 5 and the existing GSF, we got the following results:
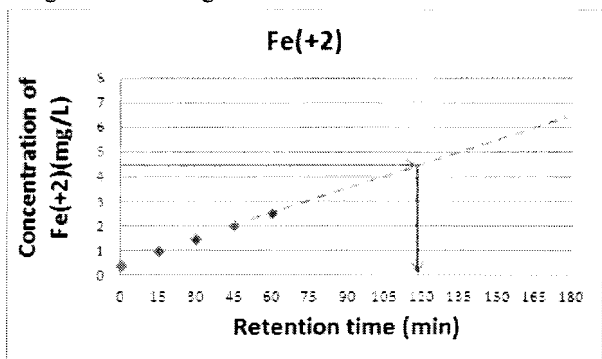
Fig.4 Increase of ferrous iron in laboratory tests
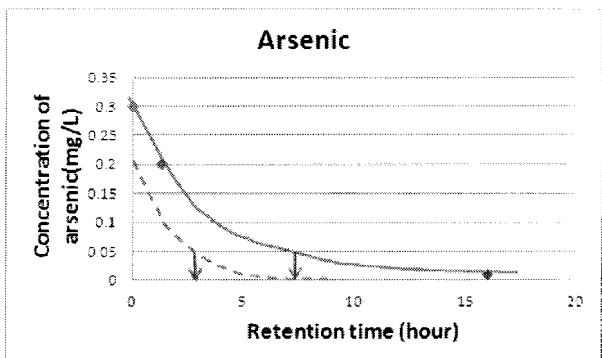

Fig.5 Decrease of arsenic concentration in laboratory tests

1) The number of iron metal of 1m is 88.

2) The assumed value of Fe=4.5ppm during 2 hours by Fig.4 is enough realized in GSF during pumping time from morning to evening & evening to next morning, and morning to noon & noon to evening even if villagers use GSF in the noon.

3) Arsenic concentration will decrease in the inlet tank

from Fig.5, though arsenic is to be co-precipitated with iron at the gravel voids in gravel tanks. In the villages of Muzaffargar, this may play an effective role, because that the GSF is to be installed with tube wells of As=200ppb. It means about 3~4 hours needed for decrease of arsenic concentration until 50ppb as shown in the dotted line of Fig.5. The decrease of arsenic concentration may happen in enough at the inlet tank of GSF.

4. CONCLUSION

Punjab region is semi-arid climate and has the world' largest canal network for irrigation. The situation of groundwater in aquifer is, therefore, complicate through the evaporation of groundwater and the recharge of groundwater by leakage from canals and return from irrigation water.

The elevation of salts in the groundwater by evaporation may raise the arsenic concentration. The recharging water, which has raised water levels and created shallow aquifer body, may cause to increase the level of oxidizing in the groundwater.

Also, in the Punjab region, the arsenic contamination seems to be caused by anthropogenic pollutants on the ground surface, such as fertilizers in agriculture and wastes from industry & household.

These phenomena are likely to happen in the shallow aquifer and the older deep aquifer has different composition of groundwater. Both of groundwater may be mixed in partially through installation of deep tube well, because that the stratum in Punjab region is composed of fine to coarse sand with little intercalated silt or clay.

Pakistan is developing country with low public safety. There seems not to be installed arsenic-safe water units at community levels. The tap water in the NICCO office showed 0.3ppm of arsenic concentration, which is drunk through a usual domestic filter.

Pakistan people are asking the assists from foreign countries to get safe water. Although the arsenic problems are so complicate in Pakistan, we should try to mitigate arsenic contamination for them, who have lived in the double danger, the low public peace and no safe water.

In the research, good results were obtained, through which the arsenic removal unit, GSF is now under construction.

ACKNOWLEDGEMENTS

REFERENCES

AAN and Research group for arsenic contamination by Arsenic in the Mekong River Delta, (2012). Groundwater arsenic contamination of groundwater in the Mekong River Delta, The Association for Geological Collaboration in Japan, Monograph 58, 1-151pp.

Abida.Farooqi, Harue Masuda, Minoru Kusakabe, Muhammad Naseem and Nousheen Firdous, (2007). Distribution of highly arsenic and fluoride contaminated groundwater from east Punjab, Pukistan, and the controlling role of anthropogenic pollutants in the natural hydrological cycle, Geochemical Journal, vol.41, 213-234pp.

H. Yokota, (2006). Basics to application of groundwater and soil contamination, Chapter 10 Arsenic contamination overseas, edited by Japanese Association of Groundwater Hydrology, Riko Tosho, 223-251pp.

Hussainuzzaman, M. and Yokota, H. (2006). Efficiency of Arsenic Removal Unit working in Bangladesh and Cement Stabilization of its Sludge, Journal of ASTM International, Vol.3, No.4, 1-9pp.

JICA & AAN, (2004). Integrated Approach for Mitigation of Arsenic Contamination of Drinking Water in Bangladesh, Final Report, November.

Kyung Hwa Cho, Suthipong Sthiannopkao, Yakov A Pachepsky, Kyoung-Woong Kim, Joon Ha Kim, (2011). Prediction of contamination potential of groundwater arsenic in Cambodia, Laos, and Thailand using artificial neural network, Water Research, 08/2011; 45(17):5535-5544pp.

Kyoung-Woong Kim, Penradee Chanpiwat, Hoang Thi Hanh, Kongkea Phan, Suthipong Sthiannopkao, (2011). Arsenic geochemistry of groundwater in Southeast Asia, Frontiers of medicine, 12/2011,5 (4), 420-433pp.

Ministry of Local Government (Bangladesh) and JICA, (2008). Sustainable Arsenic Mitigation under Integrated Local Government System in Jessore, FINAL REPORT, November.

Muhammad Akram Kahlown, Muhammad Aslam Tahir, Hifza Rasheed and Iram Anwar, (2003). Arsenic

Contamination of Groundwater in Southern Punjab PCRWR,-UNICEF Joint Venture.

Research group for arsenic contamination of groundwater in Inner Mongolia, (2007). Arsenic contamination of groundwater in the Hetao plain of Inner Mongolia, China,The Association for Geological Collaboration in Japan, Monograph 56,1-125pp.

R.B.Sah, (2002). Arsenic Research Committee, Department of Geology, Tribhuvan University : Studies for possible natural sources of Arsenic poisoning of Groundwater in Terai Plain of Nepal,October.

R.T.Nickson, J.M..McArthur, B.Shrestha, T.O.Kyaw-Myint and D.Lowry, (2005). Arsenic and other drinking water quality issues, Muzaffargarh District, Pakistan, Applied Geochemistry, 20, 55-68pp.

Yasunori Yano, Akihiko Kodama, Koichiro Shiomori, Mitsuhiro Sezaki, Kimiko Tanabe, Rakesh Jaiswal, Piyush Jaiswal, Tripathi and Hiroshi Yokota, (2009). Arsenic Contamination of Groundwater at Uttar Pradesh state in India, International Symposium on Geo-disaster Prevention and Geo-environment in Asia, JS-Fukuoka, The Japanese Geotechnical Society,

193-198pp.

Yasunori Yano, Kenichi Ito, Akihiko Kodama, Koichiro Shiomori, Shigeki Tomomatsu, Mitsuhiro Sezaki and Hiroshi Yokota, (2012). Arsenic Polluted Groundwater and its Countermeasures in the Middle Basin of Ganges, Uttar Pradesh state, India, Open Journal JEP, 2A, 856-862 pp.

Yokota, H., (2004). Arsenic pollutions of groundwater in the world and arsenic removal unit installed in Bangladesh, Keynote Lecture, Vietnam-Japan Joint Seminar on Geotechnics and Geoenvironment Engineering, Hanoi, November, 226-242pp.

Yokota, H. et al., (2006). Collaboration between NGO and University of Miyazaki and Asian Arsenic Network for the mitigation of arsenic contamination in Ganges basin, Proc. of 1st Intern. Symp. on Health Hazards of Arsenic Contamination of Groundwater and its Countermeasures, keynote lecture, 47-58pp.

World Bank, (2005). Towards a More Effective Operational Response, Arsenic Contamination of Groundwater in South and East Asia Countries.

APPENDIX

Appendix Water quality of tube well in Ghazi Ghaat, Muzaffargar, Pakistan (well depth=80m)

Code	pH	TDS	T°C	Zn (µg/L)	As (mg/L) 2011	As (mg/L) 2012	NO3-N (mg/L)	NH4-N (mg/L)	Ca (mg/L)	Cl (mg/L)	F (mg/L)	Fe2+ (mg/L)	Mg (mg/L)	PO4-P (mg/L)	K (mg/L)	SO4 (mg/L)	ORP (mV)
1	7.2	626	29	192	0.05	0.01	0.3	UR	33	12	UR	0.03	10.8	0.08	18.4	65	-98
2	7.8	852	34	180	0.05	0.05	UR	UR	83	31	0.52	0.08	31.8	0.05	14.3	70	-138
3	6.3	578	29	323	0.05	0	3.1	0.04	66	38	UR	0.04	29	0.04	21.8	82	-59
4	6.5	448	27	24	0.1	0.05	UR	UR	49	21	UR	0.02	24.1	0.05	13.7	95	-68
5	6.4	585	30	UR	0.5	0.4	0.7	UR	74	17	0.11	0.07	51.4	0.16	17.6	85	-96
6	6.3	531	30	98	0.05	0.2	1.4	0.09	84	8	UR	0.09	30.6	0.08	10.7	70	-100
7	6.9	373	30	63	0.05	0.05	UR	UR	12	8	0.44	0.09	14.3	0.05	9	43	-171
8	6.5	417	30	84	0.05	0.05	0.8	UR	48	6	UR	0.13	23.4	0.07	10.3	47	-165
9	6.5	400	28	260	0.1	0.1	UR	UR	67	9	UR	0.05	21.3	0.07	9.2	30	-135
10	6.5	401	29	136	0.05	0	UR	0.03	61	7	UR	0.04	20.3	0.07	10.1	30	-155
11	6.5	432	31	98	0.1	0.01	UR	UR	58	9	UR	0.07	22.7	0.03	9.8	49	-115
12	6.3	615	28	108	0.1	0.1	0.4	0.16	101	36	UR	1.41	36.5	0.07	12.9	153	-140
13	6.5	435	29	67	0.1	0.05	UR	0.28	71	11	0.13	0.11	26	0.04	11.2	68	-115
14	6.9	352	30	44	0.1	0.1	0.7	UR	25	12	UR	0.1	31.2	0.09	10.4	55	-12
15	6.7	542	31	5	0.3	0.1	0.4	UR	36	17	UR	0.12	41.5	0.12	11.4	95	-13
16	7	463	29	23	0.05	0.05	UR	UR	19	22	0.1	0.08	22.4	0.10	9.9	82	-125
17	7.6	610	32	41	0.05	0.05	UR	0.02	47	23	0.09	0.06	19.6	0.05	12.1	78	-106
18	7.7	648	34	671	0.05	0.05	UR	UR	33	28	0.11	0.15	19.3	0.03	10.7	82	-161
19	7.7	831	33	921	0.05	0.05	1.1	UR	70	41	UR	0.2	40.1	0.10	12.2	70	-132
20	7.6	797	30	825	0.05	0.05	0.6	UR	54	53	UR	0.2	28.4	0.06	20.9	178	-145
21	8.7	660	30	OR	0.1	0.1	1.3	0.1	UR	7	UR	0.01	4.5	1.18	3.4	78	-10
22	7.6	1364	31	381	0.05	0	0.4	0.04	30	142	0.3	0.49	14.5	0.03	7.8	245	-133
23	7.6	724	33	834	0.05	0.2	UR	UR	58	8	UR	0.23	27.2	0.17	9.4	55	-128
24	6.8	270	29	38	0.05	0.1	1.2	UR	31	11	0.19	0.1	11.2	0.05	5.9	49	-145
25	6.7	420	28	31	0.05	0.05	0.8	UR	57	41	0.08	0.05	19.4	0.06	8.8	78	-169
26	7.4	309	28	OR	0.05	0.05	0.4	UR	47	23	UR	0.08	19.4	0.07	7.9	63	-154
27	7.1	240	28	OR	0.05	0.05	0.5	0.02	27	6	0.14	0.08	18.4	0.08	6.5	56	-81
28	6.9	211	28	32	0.05	0.05	UR	0.02	15	UR	0.08	0.09	12.1	0.08	5.6	23	-99
29	7	207	29	OR	0.05	0.025	UR	UR	25	UR	0.15	0.07	14.5	0.08	5.8	25	-85
30	7	235	28	429	0.05	0.1	2	UR	127	UR	0.09	0.06	11.7	0.02	5.4	35	-91

Appendix. (continued)

Code	pH	TDS	T°C	Zn (µg/L)	As (mg/L) 2011	As (mg/L) 2012	NO3-N (mg/L)	NH4-N (mg/L)	Ca (mg/L)	Cl (mg/L)	F (mg/L)	Fe2+ (mg/L)	Mg (mg/L)	PO4-P (mg/L)	K (mg/L)	SO4 (mg/L)	ORP (mV)
31	7	210	28	OR	0.05	0.025	0.4	UR	19	UR	UR	0.09	13.8	0.08	6.o	32	-93
32	6.9	348	29	35	0.05	0.05	UR	0.06	23	UR	UR	0.05	14.9	0.05	6.7	33	-130
33	6.4	750	30	85	0.1	0.05	UR	0.02	25	9	0.33	0.06	17.7	0.04	10.3	34	-124
34	6.8	340	28	31	0.05	0.1	UR	0.16	89	81	UR	0.08	48.7	0.07	16.8	161	-118
35	6.8	340	29	30	0.1	0.01	UR	UR	34	8	UR	0.07	12.7	0.04	11.3	39	-137
36	6.8	339	29	76	0.05	0.01	0.6	UR	27	8	UR	0.03	13.2	0.10	7.8	67	-94
37	6.8	340	29	83	0.05	0	UR	0.01	30	9	0.15	0.06	12.4	0.10	8.o	31	-68
38	6.8	340	29	OR	0.1	0	UR	UR	32	20	0.13	0.03	11.7	0.04	7.5	51	-97
39	8	626	28	OR	0.1	0.2	UR	UR	48	88	UR	0.14	25.3	0.05	10.6	30	-155
40	8.2	332	29	38	0.1	0.05	UR	0.02	24	UR	0.25	0.04	16.1	0.06	9.3	19	-110
41	7.9	931	31	40	0.1	0.025	0.5	0.01	76	168	UR	0.08	26.9	0.07	11.6	132	-144
42	7.7	634	29	617	0.1	0.025	1.3	UR	67	70	UR	0.04	24.7	0.05	10.7	71	-97
43	7.6	1037	32	35	0.1	0.1	UR	0.07	43	79	0.33	0.03	17.4	0.05	10.5	169	-144
44	7.7	656	30	86	0.05	0.05	UR	0.05	56	40	UR	0.07	36.8	0.05	12.9	64	-131
45	7.6	850	30	82	0.05	0.05	0.5	0.04	59	94	UR	0.17	41.9	0.07	12.7	133	-144
46	7.8	835	32	36	0.05	0.1	0.3	0.05	67	134	UR	0.06	31.5	0.06	9.8	138	-137
47	7.9	604	35	32	0.05	0	0.6	0.07	53	70	0.17	0.1	17.1	0.07	8.5	83	-174
48	7.7	604	35	37	0.1	0.01	UR	0.05	106	142	UR	0.08	22.6	0.03	13.1	150	-138
49	7.7	494	36	66	0.05	0	0.4	UR	43	80	0.24	0.04	11	0.06	6.8	47	-110
50	7.6	814	31	46	0.05	0.2	0.6	UR	81	40	UR	0.19	36.3	0.09	11.7	131	-141
51	7.4	968	29	39	0.1	0.2	0.5	0.04	65	36	UR	0.22	29.2	0.11	13.7	105	-135
52	6.7	660	34.1	375	0.1	0.025	0.7	0.03	23	64	UR	0.06	20.6	0.03	10.3	43	-133
53	6.8	510	29.3	124		0	0.3	0.12	57	40	UR	0.04	16.5	0.03	12.4	149	-45
54	6.8	491	30.1	134		0.1	UR	0.02	60	60	UR	0.06	13.8	0.05	11.6	80	-111
55	6.7	628	30.6	UR		0.025	UR	UR	65	60	0.22	0.33	16.5	0.07	10.8	98	-119
56	6.8	543	29.1	119		0.01	1.1	0.12	58	75	UR	0.04	14.7	0.05	9.4	105	-107
57	6.6	557	30.6	151		0	0.9	UR	56	92	UR	0.14	18.5	0.06	11.5	144	-137
58	6.6	782	30.7	68		0.01	0.5	UR	63	99	UR	0.06	22.7	0.03	14.8	222	-78
59	6.6	700	28.3	158		0.025	1.6	0.03	77	66	UR	0.09	22.8	0.03	12.4	214	-85
60	6.7	580	30.9	197		0.05	UR	0.24	61	52	UR	0.05	14.4	0.05	13.9	151	-125
61	6.7	786	30.6	OR		0	UR	0.05	114	111	UR	0.06	32.6	0.04	12.1	249	-75
62	7.5	920	30	OR		0.05	2.2	0.21	117	59	UR	>2.0	33.6	0.05	9.9	189	-144
63	7.4	1049	29	695		0.025	UR	0.61	24	83	UR	1.67	35.7	0.06	12.6	212	-136
64	7.6	571	30	165		0.1	1.0	0.03	57	14	0.10	0.14	20	0.04	10.1	79	-143
65	7.6	593	30	316		0.05	0.5	UR	63	12	0.56	0.05	22	0.05	9.4	63	-140
66	7.5	707	31	62		0	0.9	0.01	70	28	UR	0.09	27.5	0.02	9.8	87	-131
67	7.5	669	31	88		0	UR	0.03	96	24	UR	0.11	29.7	0.05	10.2	68	-110
68	7.8	476	31	34		0.1	UR	0.18	28	UR	0.31	0.05	7.2	0.06	5.8	30	-150
69	7.7	541	29	72		0.05	1.2	0.05	16	18	0.09	0.1	13.9	0.03	7.3	67	-150
70	8	406	32	65		0.05	1.3	0.06	23	24	0.16	0.14	10.6	0.04	8.7	16	-140
71	7.6	735	31	172		0.05	0.5	UR	62	40	0.23	0.2	18	0.06	7.5	127	-165
72	7.6	613	31	UR		0	UR	UR	43	20	0.11	1.27	31.5	0.03	10.o	79	-134
73	7.5	930	32	25		0	0.5	UR	71	75	UR	0.07	35.3	0.02	14.o	177	-114
74	7.5	1046	30	59		0	UR	0.02	123	85	UR	0.25	36.1	0.02	17.1	203	-96
75	7.5	1023	31	77		0.01	UR	0.04	82	106	UR	0.19	13.9	0.01	15.1	199	-130
76	7.5	1009	32	262		0.01	UR	0.08	56	22	0.09	0.04	25.8	0.01	18.9	122	-132
77	7.6	808	31	OR		0	1.8	UR	60	75	0.18	0.05	31.6	0.03	31.0	165	-97
78	7.7	810	31	OR		0	0.3	UR	74	61	UR	0.32	27.8	0.03	13.6	157	-128
79	7.6	810	31	569		0.01	0.03	0.03	88	48	0.79	0.05	31.4	0.03	15.6	65	-141
80	7.3	1223	31	OR		0.05	3.6	0.37	137	118	0.15	0.09	49.4	0.09	14.8	219	-122