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The Drinking Water Quality in Four Physiographic Regions of Nepal and Arsenic Contaminated Groundwater in Terai, Lowland Nepal

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1. Introduction

This paper will provide an overview of drinking water quality of the study areas in Nepal and we will discuss the issues regarding arsenic contamination in Terai.

UNICEF has identified that Nepal has successfully cut infant mortality rate (IMR) by two thirds in the last one and a half decade in 2007. However, Dr. S. Sakai, UNICEF representative, noted that some 65,000 children under five still died each year in Nepal (UNICEF, 2006). The up-dated IMR of Nepal was provided by CIA. The IMR, the number of deaths of infants under one year old in a given year per 1,000 live births, was 63.66 deaths/1,000 live births. IMR of Japan is only 2.8 deaths/1,000 live births (CIA, 2007).

Infant mortality depends on the quality of drinking water. Disease caused by drinking water has been serious problems in Nepal. Most pollutants are stemming from human and animal wastes, agricultural runoff, sewage, and domestic waste effluents.

By the end of 20th century many people living in Terai (Tarai), lowland Nepal, had been utilizing surface water as drinking water, including water of rivers, ponds, irrigation canals, and reservoirs for irrigation. The microbiological contamination of the surface water, along with a high prevalence of malnutrition, often caused the diarrhea and killed lots of infants, especially in Terai.

The domestic and international entities including UNICEF as well as central and local government supported constructing tube wells to improve the drinking water quality. Thanks to the clean drinking water of tube wells, recent IMR was dramatically improved as announced by UNICEF. However, many aquifers have been identified to be highly contaminated with arsenic since 1999, still many people depends on the contaminated groundwater.

Such arsenic contamination was called hyperbolically as "the largest mass poisoning of a population in history" (Atkins et al., 2007). Dangerous arsenic concentrations in natural waters are now a worldwide problem and it also referred to as a 20-21st century calamity (Mohan and Pittman, 2007). Well-known high-As (arsenic) groundwater areas have been found in Argentina, Chile, Mexico, China and Hungary, and in West Bengal (India), Bangladesh and Vietnam (Smedley and Kinniburgh, 2002). High arsenic concentrations have been also reported recently from the USA, China, Chile, Bangladesh, Cambodia, Taiwan, Mexico, Argentina, Poland, Canada, Hungary, Japan and India (Mohan and Pittman, 2007).

The official report, 'Nepal's Arsenic Interim Policy and Preparation Report 2001 ' made by His Majesty's Government is one of the oldest records on arsenic contaminations and it reported that the Department of Water Supply and Sewerage and WHO conducted sample testing and found arsenic in the tube wells for drinking water.

As a part of our general environmental studies of Nepal, Mountain and Hill areas, and southern lowland area called Terai, were investigated in 2007. Highly arsenic contaminated drinking water was identified at Parasi (Sarawal) in Nawalparasi district locating in the alluvial plain altitude between 103 m and 115 m.

2. Natural Environment of Nepal

2-1. Geographical Setting of Nepal

Our study areas in Nepal are located in the four major different physiographic districts, namely, the Mountain, Hill, Siwalik, and Terai (Fig. 1). The Himalayan Mountains, extending about 2400 km from east to west, were created by the collision of India and Eurasia continent. The collision has also thickened the crust of Hill/Middle-Mountain and Siwalik. Terai is a lowland consisting of alluvial deposits.

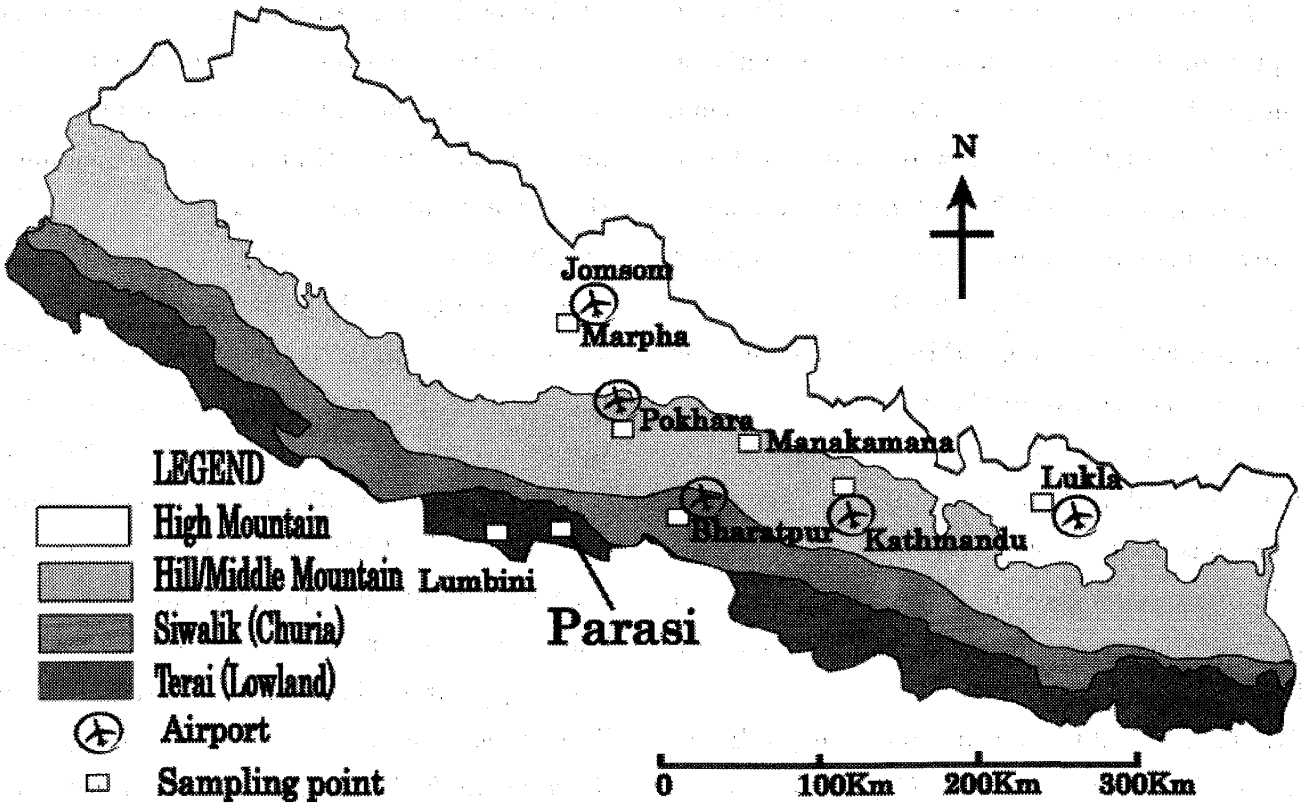

Fig.1 Physiographical division and the sampling/study areas in Nepal.

2-2. Physiographic and Geological Features

In the Mountain region, we investigated Lukla-Namuche area which is adjacent to Mount Everest (Sagarmatha) and Jomsom-Marpha area adjoining to Annapurna Mountains. Both areas are ravines surrounded by the high mountains exceeding 6,000 m ~ 8,000 m.

Kathmandu, Manakamana (near Gorkha) and Pokhara are located in the Hill area. Bharatpur is located on the Siwalik Fold Belt. The southern lower land area including Parasi (Sarawal) and Lumbini belong to Terai.

The age of these four areas becomes younger from north to south (Fig. 1). The Himalayan Mountains consist of highly metamorphosed rocks including granite and gneiss has the oldest formations in Nepal, while Terai has the youngest alluvial formations. The hilly midland belt between the Himalaya and Siwalik is composed of mainly clastic and carbonaceous rocks and dykes.

Siwalik, also called Churia Range, is made of mainly coarse fluvial deposits including silt, sandstone, shale, and conglomerate. The Siwalik hills are mostly composed of alternating beds of sandstones and mudstones (Tamrakar et al., 2002).

The alluvium sediments of Terai consist of molasse, mainly clastic sediments including mudstone, sandstone, and conglomerate. The layers are composed of boulders, gravels, sands, silt, and clays. Terai Plain is underlain by a thick, relatively flat-lying sequence of Mid to Late Tertiary molasse (Siwalik Group) which uncomformably overlies subbasins of early Tertiary to Protorozoic sediments (Surkhet, Gondwana and Vindhyan Groups) and igneous and metamorphic rocks of the Indian Shield (Friedenreich et al., 1994).

2-3. Thrusts and Folds in Terai

All area including alluvial plains of Nepal has been influenced by thrusts and folds. As Upreti (2000) explained, the Terai alluvial plain also belongs to the Tectonic Zone, which consists of over one km of recent alluvium concealing the Siwalik Group (Churia) and underlying rocks of northern Peninsular India. Recently active southward-propagating thrusts and folds beneath Terai have affected both the underlying Siwalik and the younger sediments, which made up with very complex geological structures.

2-4. Climate

Nepal climate is basically corresponding to topographic altitude as shown in Table 1. Mountain area is partly temperate, but mostly cold, and subarctic/arctic zone according to its altitude. The higher area is sometimes called 'tundra and alpine' climate. Hill area is basically temperate zone with cool to moderate climate. It is often called 'warm temperate and cool temperate' region. Terai belongs to tropical and subtropical zones.

2-5. Mean Temperature

Temperature of January ranges from –30℃ to 18℃ in Nepal. Winter temperature in Terai, Siwalik, and river basins ranges from 12℃ to 18 ℃ and Hill indicates 6 ℃ to 9 ℃. The temperature of Mountain goes down according to altitude. Temperature of July ranges from −3℃ to 35℃. Southern Terai experiences very hot weather in summer with 27℃ to 30℃, sometimes up to 35℃ in Western Terai. The Hill region records 20℃ to 25℃ in summer.

Analyses of maximum temperature data from

49 weather stations in Nepal for the period 1971-94 revealed warming trends (Shrestha et al., 1999). Such trend is still on-going as we confirmed with the Nepal Meteorological Agency in 2007.

Table 1　Annual weather data (normal) in the each investigation region in Nepal

Index No	Stations	(m)	Precipitation (mm)			Temperature (℃)		
		Elevation	Annual	Monsoon	Winter	Maximum	Minimum	Mean
601	Jomsom	2744	262	136	29	17.5	5.3	11.4
1103	Jiri (near Lukla)	2003	2268	1844	52	19.9	8.4	14.2
1030	Kathmandu	1336	1437	1123	46	24.8	11.7	18.1
809	Gorkha (near Manakamana)	1097	1764	1369	54	—	—	—
804	Pokhara	827	3951	3126	79	26.3	15.2	20.6
902	Rampur (near Bharatpur)	256	1923	1583	48	30.6	17.4	24.0
705	Bhairahawa (near Parasi)	109	1671	1443	45	30.7	18.5	24.6

2-6. Annual Mean Precipitation

Pokhara region is famous for its extraordinary heavy rain, with more than 4,000 mm annual mean precipitation. The mean annual precipitation is more than 5,000 mm in the southern slope of the Annapurna Range, 10～30 Km in the north of Pokhara (Fig. 2). However, in the central Himalaya, the Mustang (including Jomsom area) has less than 250 mm precipitation where indicating the least forested topography. It rarely rains even in the monsoon season. Terai has more or less 1,500 mm precipitation in a year.

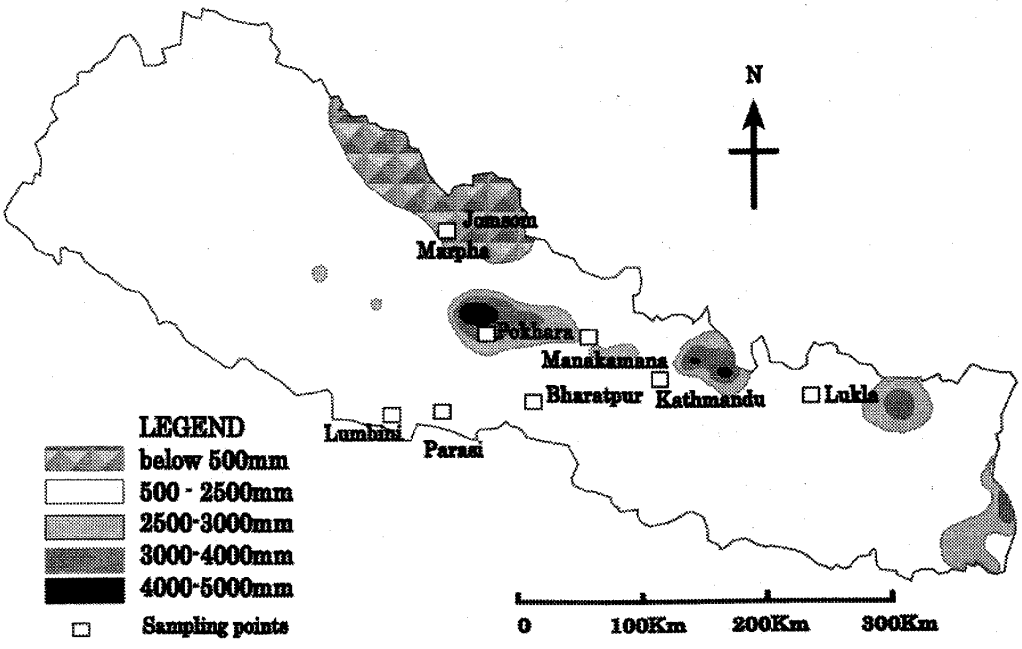

Fig.2　Annual mean precipitation in Nepal.

The precipitation generally deceases from central part towards west. In the Mountain the precipitation occurs mostly in the form of snow. Locally, south facing slopes receive higher precipitation. Most rain falls in the monsoon season (4 months) in summer. In the meantime, the precipitation in winter is very few.

3. Arsenic Contamination

3-1. Short History of Arsenic Contamination

In 1982 groundwater arsenic contamination in West Bengal (India) was first reported. In Bangladesh arsenic was first detected in the West-Bengal district of India in 1993 and the arsenic victims caused by contaminated groundwater were identified in Bangladesh by 1995. Highly As contaminated groundwater were found in many areas in the world.

3-2. Arsenic Contamination in Nawalparasi

In Nepal the first study on arsenic contamination in Terai was conducted in 1999 by the Department of Water Supply and Sanitation (Maharjan et al., 2005). According to the ENPHO Annual Report 2005, from September to December 2004, ENPHO in partnership with Asian Arsenic Network, Japan, Kyushu University and University of Miyazaki, Japan, conducted arsenic testing and health survey in Nawalparasi district.

Maharjan et al. (2006) also reported on arsenicosis surveys during 2001-2004 and confirmed that the highest prevalence (18.6%) of arsenicosis was found at Patkhouli Village of Nawalparasi, where 68 tube-wells (95.8% of tested 71 wells) were contaminated with arsenic. The arsenic concentration was over 0.05 mg/L according to the ENPHO Annual Report 2005. Further, Maharjan et al. (2006) reported that all 63 tested tube-wells at Goini village in Nawalparasi indicated arsenic contamination and the prevalence of arsenicosis was 11.3% (56 out of 495). Therefore, Goini was selected one of our study sites.

4. Results

4-1. Values of pH

In Nepal four different locations were selected as our study sites (Fig. 1). The water samples were analyzed and we found the major difference in pH values in two Mountain areas. In Lukla – Namche area, we identified relatively low pH values (<6.7) and Jomsom area we confirmed higher pH values of 8.0 or more (>8.0), as shown in Fig.3. The pH values in Kathmandu are same level as one in Lukla – Namche area. The value was measured by pH meter (MP-230) made by Mettler Co. and EC was measured by electric conductivity meter (CM-60S) made by Toa Electronics Co. Ltd.

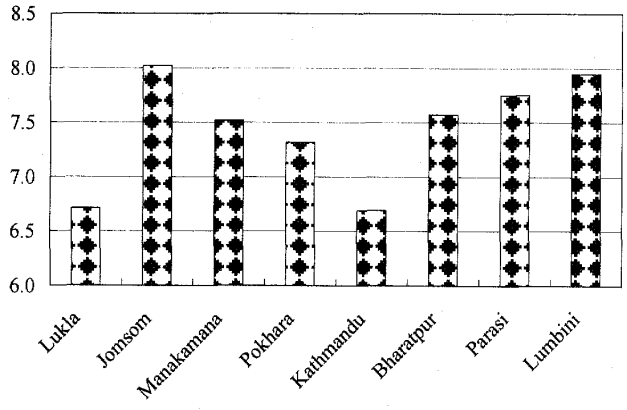

Fig.3 The mean value of pH in the investigated area in Nepal.

Contaminated stream water may influence the water quality in Kathmandu. Other area indicated 7.3~8.0 as pH values. The sampled groundwater in Parasi and Lumbini showed mostly alkaline pHs. Lukla and Kathmandu

indicated moderate acid pHs but other area especially Jomsom, Lumbini, and Parasi indicated alkaline pHs (Fig. 3).

4-2. Chemical Analysis

The water quality was surveyed and indicated very interesting results (Table 2). On the cationic concentration, Lukla water indicated the best quality with less than 10 mg/L. This is because the rain water will not be influenced by local minerals or sediments. Parasi and Lumbini indicated high concentrations, between 125-140 mg/L. Samples of Manakamana and Pokhara, both river water, indicated less than 20mg/L. However, Jomsom showed higher concentrations of about 60 mg/L which suggests that the local geology is not massive metamorphic/crystalline rocks but weathered calcium containing soils, i.e., marine sediments. The component in the water was analyzed by the ion chromatograph (LC-10A) made by Shimadzu Co. Ltd.

Table 2　Water quality survey results (mean value) in the investigated areas in Nepal

Area	EC	pH	Na	NH4	K	Mg	Ca	Cl	SO4	Hardness
	μS/cm		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Lukla	20.7	6.71	0.61	0.14	0.44	0.32	3.72	0.14	0.44	10.63
Jomsom	308.5	8.02	0.75	0.16	0.40	11.24	44.66	0.17	29.15	157.76
Manakamana	135.8	7.52	5.30	0.25	0.79	2.65	6.44	1.08	0.42	26.97
Pokhara	74.3	7.32	1.47	0.17	0.50	1.31	12.51	1.03	1.51	36.64
Kathmandu	455.5	6.69	30.94	11.69	3.08	5.94	29.70	0.73	51.58	98.63
Bharatpur	151.5	7.57	4.87	0.19	0.63	3.81	22.61	2.81	6.25	72.15
Parasi	634.0	7.75	27.28	0.70	1.30	18.06	85.13	2.17	1.44	286.87
Lumbini	611.0	7.94	40.38	0.42	1.39	25.36	62.55	0.36	1.87	260.36

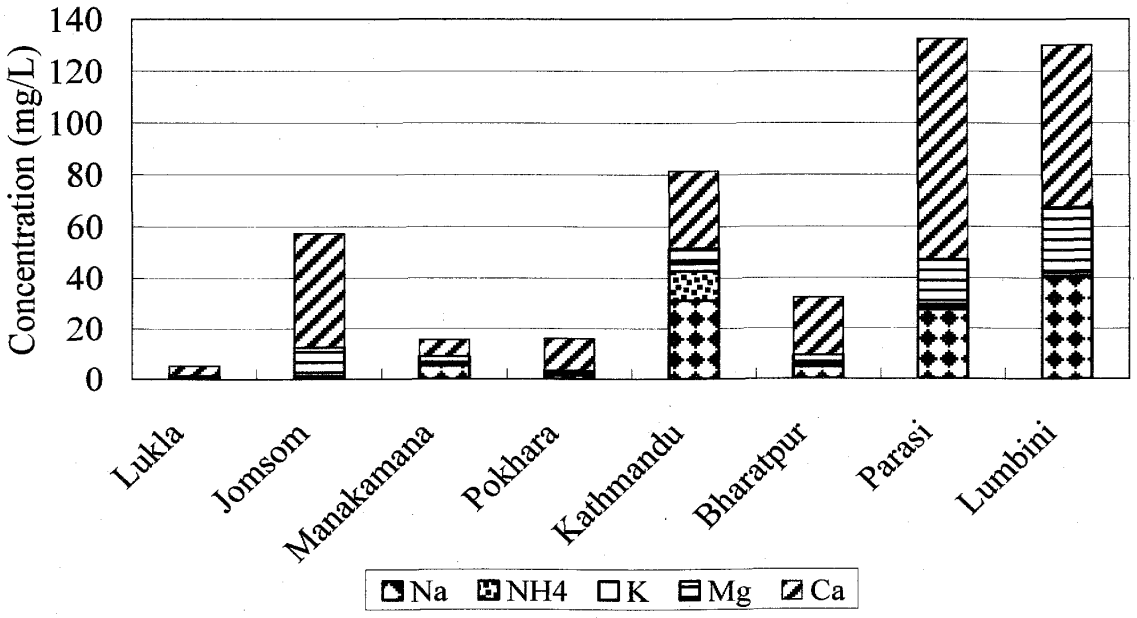

Fig.4 The mean value of component concentration (cation) in the investigated area in Nepal.

Samples of Parasi and Lumbini, both located in Terai, have higher concentrations of magnesium and calcium, however, Bharatpure data showed less concentration (about 35mg/L, a quarter of Parasi and Lumbini concentration) of magnesium and calcium. Bharatpure locates in Siwalik Hill area, not in Terai.

Table 3 The water quality standard for drinking water

	JAPAN	WHO	USEPA MCL
Arsenic	0.01	0.01	0.05
Sodium	200	200	—
Chlorine ion	200	250	250
Hardness	300	—	—
pH	5.8～8.6	—	6.5～8.5

(mg/L)

USEPA : U.S. Environmental Protection Agency

M C L : Maximum Contamination Level

Our investigation on NH_4^+ in Nepal has proved that drinking water sampled at Kathmandu showed about 10% share (weight) of its contaminants (Table 2 and Fig. 4). Other area showed no detective data on NH_4^+. As Murcott & Lukacs (2002) suggested, nitrate contamination will be more common in urban than in rural agricultural areas. Further, as we confirmed at Parasi, tube wells shallower than 5 m -10 m were more likely to be contaminated with nitrate than deep wells. Some of the nitrate sources may be excreta of human/animals, manure, and fertilizer in rural areas.

4-3. Component Analysis

Residence time in aquifer sediments may influence the ground water quality and its soluble components, however, diluted groundwater still have similar nature of water quality even though the concentration will decrease dramatically. Therefore we prepared a graph showing the percentage of all soluble components (Fig. 5).

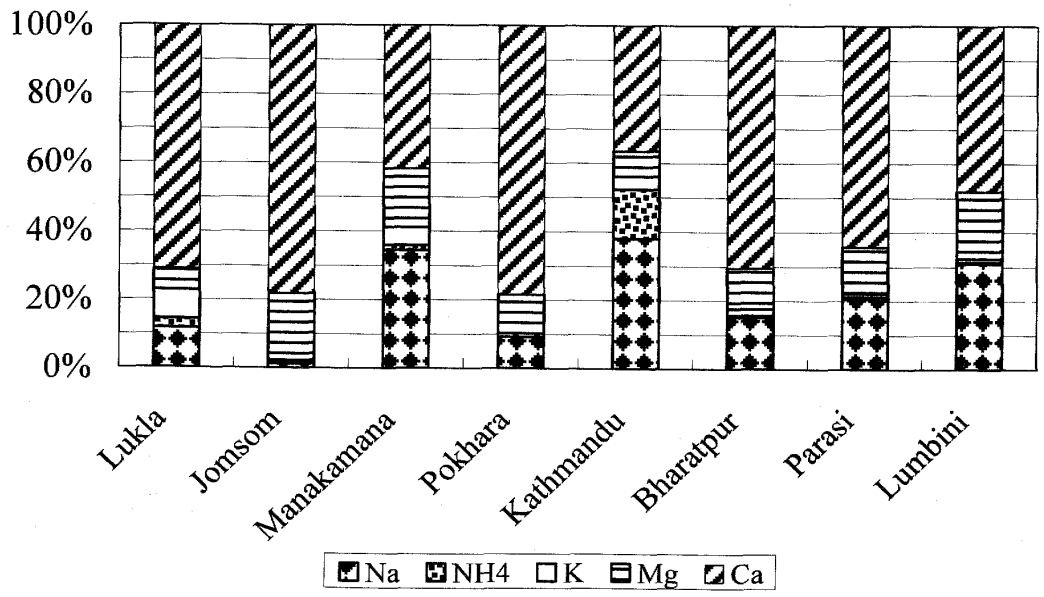

Fig. 5 The mean value of the ratio of component concentration (cation).

① Sampled water in Jomsom and Pokhara indicated more than 80% content share regarding calcium. Sampling places locate in the same drainage basin, Jomsom is upstream and Pokhara is downstream of Kali Gandaki River. Both have same headwaters geology, therefore, same water quality occurs.

② Over 30% Na and over 40% calcium was identified for both Manakamana and Kathmandu. Both locate in the Hill area, same kind of geology.

③ Though the concentration level is different, the percentage pattern of each factor is very similar for Parasi and Bharatpure.

4-4. Water Hardness

Elevated level of Mg^{2+} and Ca^{2+} contents in the groundwater sampled at Parasi and Lumbini, has indicated the worst level of drinking water quality, i.e., same as the maximum permissible contamination level in Japan of 300 mg/L (Fig. 6 and Table 3).

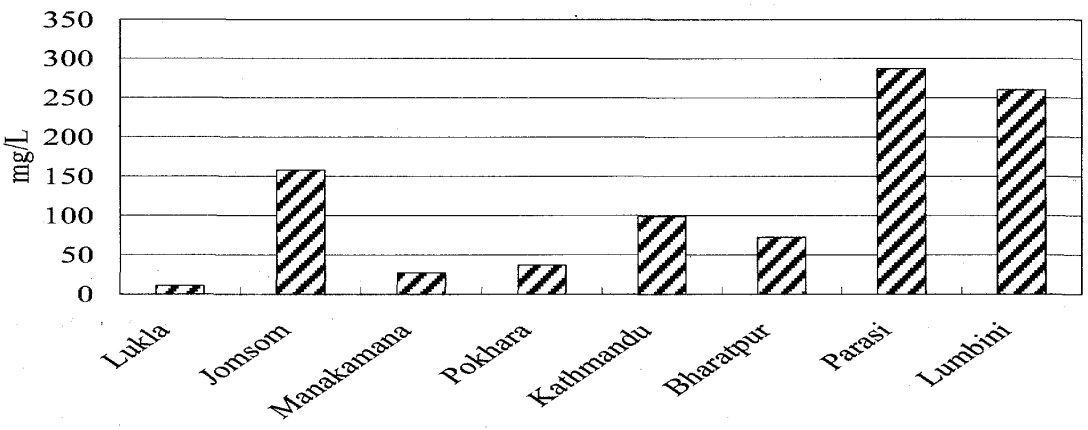

Fig. 6 The mean value of the hardness of water.

4-5. Water Quality of Terai

As indicated in Table 4, we identified various environmental indicators. The pH value was between 7.58 and 7.99 EC was 510~839μS/cm. Na^+ was 9.87~46.48mg/L. NH_4^+ was 0.23~1.66 mg/L. K^+ indicated 0.86~1.72mg/L. Mg^{2+} showed 7.95~26.37mg/L. Ca^{2+} was as rich as 58.78~103.84mg/L.

Table 4　The water quality of drinking water in each investigation region in Terai

Place	EC	pH	Na	NH4	K	Mg	Ca	Cl	SO4	Hardness
	μS/cm		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Atharahati	839	7.61	35.02	1.11	0.86	26.37	103.84	3.29	—	367.70
Sarawal	582	7.58	15.42	0.53	1.44	10.29	97.86	5.12	0.57	286.84
Goini A	719	7.67	39.90	1.66	1.71	23.04	89.35	2.32	—	317.83
Goini B	510	7.79	9.87	0.26	1.09	7.95	89.12	1.87	—	255.38
Goini C	520	7.74	9.96	0.23	1.22	8.07	90.63	1.87	—	259.65
Lumbini	609	7.90	46.48	—	1.06	23.88	58.78	0.36	1.80	244.88
Myoho temple	613	7.99	34.28	0.42	1.72	26.85	66.31	0.37	1.95	275.84

4-6. Arsenic Contamination at Parasi (Sarawal) in Nawalparasi

The arsenic concentrations of the groundwater are shown in Fig. 7, Fig. 8, and Table 5. The As contamination study area is located approximately 4 km to 9 km east and south-east of the center of Parasi in Nawalparasi. We identified the correlation of As and B (boron) as well as As and Fe. Especially, the correlation between arsenic and boron is prominent as indicated in Fig.8. The correlation coefficient between As and B by 14 samples shows 0.97. ICPM-8500 (Inductively Coupled Plasma Mass Spectrometer) was utilized for the analysis.

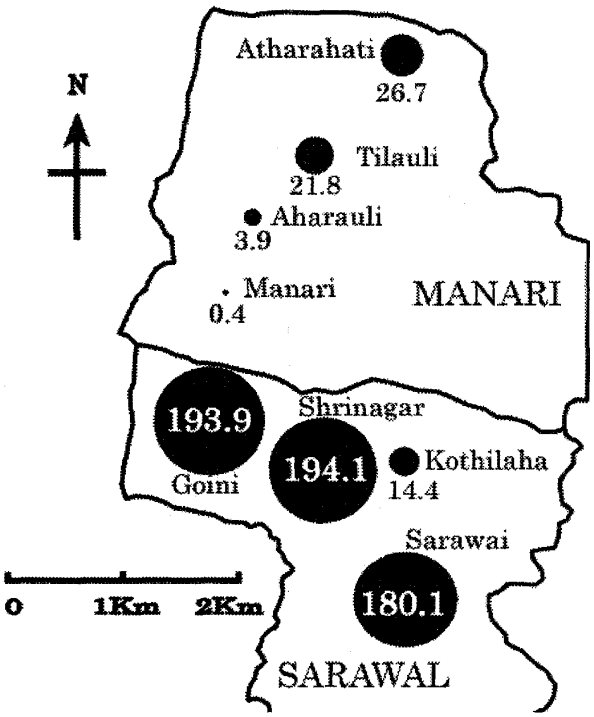

Fig.7 The arsenic concentration distribution in Parasi (unit : μg/L).

Table 5 Results of analyses of arsenic(As), boron(B), manganese(Mn) and iron(Fe) in investigation spots of Parasi

No.	Place (GW:Groundwater)	As	B	Mn	Fe
		μg/L	μg/L	μg/L	μg/L
1	Atharahati GW	26.65	6.41	299.70	13.25
2	Atharahati GW after asenic filtering	5.92	0.00	0.00	21.70
3	Atharahati GW (brown color)	15.15	2.57	447.90	45.74
4	Tilauli	21.77	0.25	244.60	42.12
5	Aharauli GW	3.94	1.03	—	47.10
6	Manari GW	0.35	0.00	0.00	49.50
7	Shrinagar GW A	193.93	21.94	40.64	65.07
8	Shrinagar GW B	188.82	21.13	39.10	54.31
9	Kothlaha GW	14.37	2.72	235.89	49.34
10	Sarawal GW A	66.19	8.39	279.80	56.26
11	Sarawal GW B	180.12	22.70	15.34	60.09
12	Goini (victim's drinking water)	194.17	22.52	7.54	59.25
13	Goini GW A	62.14	0.00	308.47	58.90
14	Goini GW B	7.54	0.00	402.07	45.97

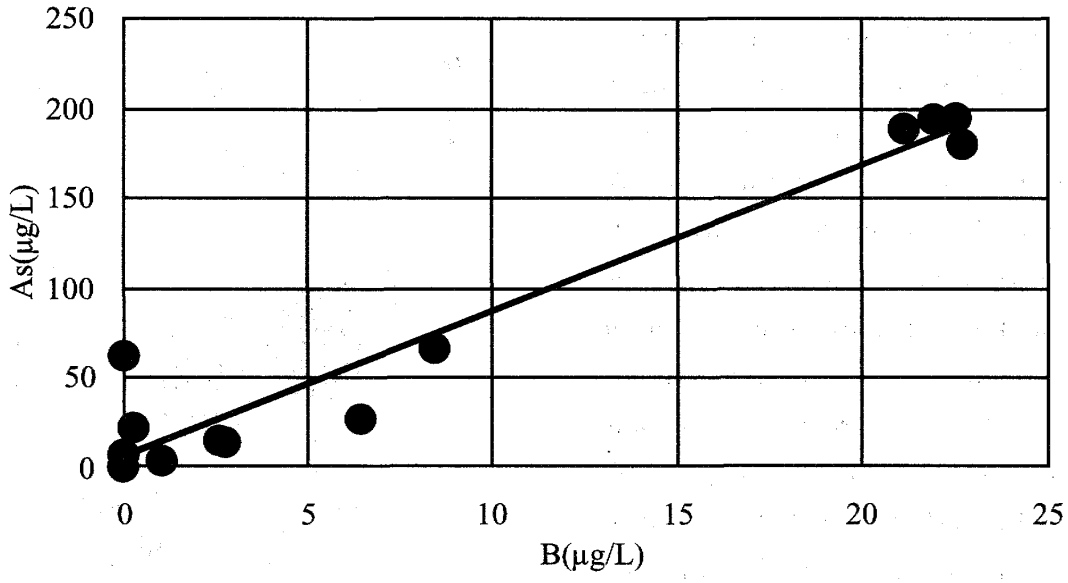

Fig.8 The correlation between boron (B) and arsenic (As).

5. Discussion

5-1. Geology of Terai and Siwalik

By reviewing the geographical features in the field with local topography maps we have noticed that no sharp increases in gradient by thrust are observed at Parasi in Terai. It is because the Terai alluvial layers are plastic, flexible, and not consolidated. However, the drainage pattern in Parasi area does not indicate normal meander patterns. The streams bend abruptly and wind their ways across the flat plain without evenly spaced loops, not uniformly spaced. Large irregularities in the meandering stream patterns are probably caused by old fold, thrust and fault of the bedrock or underlying layers, which likely resulted in very complicated drainage patterns. Also, the underground structures including local aquifers and underflow networks could have same irregularities.

Terai plain is underlain by a thick Siwalik which mainly consists of sandstones. Terai aquifers in the alluvial would be influenced by underlying Siwalik. The rock samples obtained from Mio-Pleistocene sandstone sequence of the Siwalik Group are quartzo-feldspathic to quartzo-lithic and quartzo-feldspathilithic (Tamrakar, 2007). Because steeply dipping sandstone and mudstone strata are widely distributed in the Siwalik Hills, similar structures are inferred to exist in many places (Tamrakar, 2002).

Utilizing data from the Siwalik Hills in Nepal, topographic advection on fault-bend folds was studied and suggested that drainage basins formed along the flanks of any individual linear mountain range or fault block are commonly observed to be self-similar in planform, uniformly spaced, and in some cases aligned with drainage basins on the opposing flank (Miller and Slingerland, 2006).

The similar topography of Siwalik Hills should

exist in the underground structure of Terai as shown in the Fig. 9, which may prominently influence the groundwater flow and the distribution of arsenic contamination in the groundwater of Terai. And continuing fold, thrust and fault have been twisting and distorting the aquifers in Terai just like Terai stream drainage pattern indicates. Pumping-out much groundwater out of thousands of tube wells may influence the geochemical conditions in the aquifers. Changing the balance between bedrock uplift and erosion, past and future, also influences the long-time distribution of arsenic contamination in groundwater.

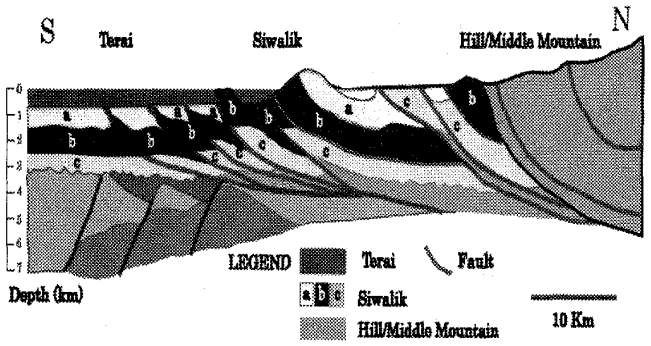

Fig.9 Siwalik geologic profile, modified the schematic figure by Friedenreich et al. (1994).

5-2. Channel Patterns

Geographical and Geological studies suggested that, in general, the higher arsenic concentrations are found in the fluvial sediments along the rivers and in the southern lowland area (Fig. 10). The original source of the arsenic contamination will be some parts of the Himalayan layers, not all parts of Himalaya. The dynamothermal metamorphism which associated with high temperatures and confining pressures created feldspathic and quartzose rocks in the Himalayan orogeny as we confirmed in Nepal. Usually such massive crystalline rocks do not contain leachable arsenic.

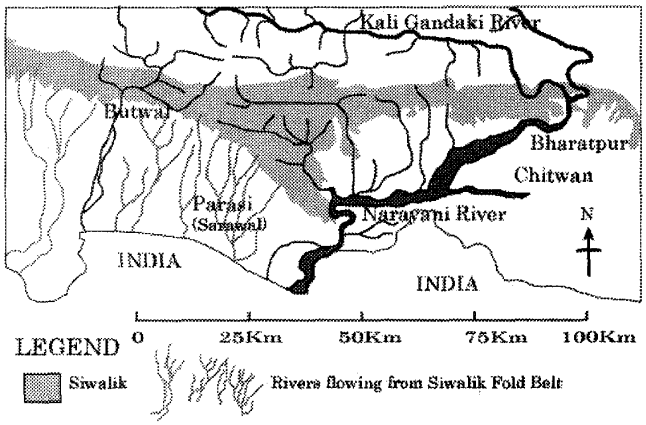

Fig. 10 Rivers flowing from Siwalik Fold Belt in Terai.

However, not metamorphosed or weathered marine sediments consist of clay, silt, and fine sand in Mustang (including Jomsom area) may contain leachable arsenic. By repeating stream erosion, transport, and deposition from north to south, finer grains will be transported to the lowland Terai. Corkscrew-like river flow erodes the outer bank of the steam and the eroded material will be deposited downstream, at the inner bank of the next bend (Chernicoff and Whitney, 2002). The surface sediments in Terai will keep moving in a long time period but underground layers including aquifer will rarely changes.

5-3. Arsenic Source

The arsenic study in West Bengal, India by Pal et al. (2002) suggested interesting findings. The Holocene sedimentary succession in a part of Gangetic alluvium, shows a fining upward sequence from medium to fine sand, silt and finally to clay and the clay layer (As = 2~31 mg/kg) contains higher concentration of arsenic

compared to the silt layer (As = 2~6 mg/kg) and the sand layer (As = 1~7 mg/kg). However, as inferred by Pat et al. (2002), the arsenic contamination in groundwater is related more with the components of sandy layer than others. Within the sandy layer in a part of West Bengal, as reported by Pat et al. (2002), the components like (i) coated iron oxyhydroxides with residual magnetite and ilmenite (As = 14~112 mg/kg), (ii) illite (As = 10~40 mg/kg), (iii) iron hydroxide-coated sand grains (As = 30 mg/kg), (iv) chlorite (As = 5~31 mg/kg), (v) biotite (As = 9 mg/kg), and (vi) siderite concretions (As = 7~9 mg/kg) store most of the arsenic and are identified as the arsenic pollutants for groundwater. Arsenic is introduced into the aquifer sediments in soluble state and get adsorbed on iron-rich clastic grains and on authigenic siderite concretions (Pal et al., 2002).

The original source of arsenic in groundwater of the Terai Alluvial Plains is leached primarily due to weathering of arsenic bearing rocks and sediments in the Himalayas (Bhattacharya, 2003). Alluvium derived from soft Plio-Pleistocene sedimentary rocks of the foothills appears to produce more groundwater arsenic than first cycle alluvium from crystalline rock higher in the Himalaya (Williams et al., 2004).

Brikowski et al. (2005) reported that the groundwater arsenic distribution is extremely heterogeneous, and in Bangladesh at the mouth of the Ganges drainage, a correlation has been noted between fine-textured surficial sediments and high arsenic content in shallow wells. Also, the same study in the Ganges headwater areas of Nepal revealed a similar correlation in the vertical direction between groundwater arsenic and clay content at well screen depth, independent of surficial sediment texture. The sediment texture-arsenic content correlation depends on redox control of arsenic mobility, and such control has been demonstrated to be the dominant mechanism of arsenic release. Presumed rapid infiltration of oxidizing waters in coarser sediments limits reductive desorption of arsenic, resulting in low groundwater arsenic concentrations. This study was conducted at an arsenic hot-spot in Nawalparasi, the highest arsenic district of Nepal and concluded that presumably at least in headwater regions coarser sediments at depth are hydraulically well-connected to the surface, and therefore support relatively oxidizing conditions (Brikowski et al., 2005).

Some of our study results were confirmed by Gurung et al. (2005). According to their paper, geological and geochemical study was carried out to investigate arsenic contamination in groundwater in Nawalparasi. The work carried out included analyses of core sediments, provenance study by rare earth elements analyses, 14C dating, and water analyses. Results showed that distribution of the major and trace elements are not homogeneous in different grain size sediments. Geochemical characteristics and sediment assemblages of the arsenic contaminated (Nawalparasi) and uncontaminated (Bhairahawa) area have been compared. Geochemical compositions of sediments from both the areas are similar; however, water chemistry and sedimentary facies vary significantly. Extraction test of sediment samples showed significant leaching of arsenic and iron. They concluded that chemical reduction and contribution from

organic matter could be a plausible explanation for the arsenic release in groundwater from the Terai sediments.

Extremely high arsenic concentrations in drinking water of the Ganges Delta (West Bengal and Bangladesh) was studied and amorphous Fe dissolution is confirmed to play an important role in the release of arsenic by Charlet et al. (2007). They reported that groundwater redox potential is controlled by the Fe(OH)3(am)/Fe2+ couple and the As(III) versus As(V) distribution (42% As(III) and 58% As(V), on average) is not at equilibrium with measured Eh values. No evidence of sulfide solid phases, such as As rich pyrite or arsenopyrite, was found (Charlet, 2007).

Most traditional explanation of arsenic contamination in Nepal was that it is primarily due to the arsenic bearing sediments derived from the Himalayas. Himal group (Pre-Cambrian) in Lukla-Namuche area, the foothills of Mt. Everest, mainly consists of feldspar, quartz, and mica. Dominant rock layers are granite, gneisses, biotite, kyanite, and thin bands of marbles, which rarely produce arsenic. No local arsenic contamination has been identified in Lukla area. As we confirmed in the field there is no evidence of sulfide mass including arsenic rich pyrite or arsenopyrite in the study areas. However, Tibetan sedimentary zone of Jomsom-Marpha contains marine sediments mainly consist of pro-delta clay, fine sand, slate, and shale. By the sedimentary facies analysis finer grains and particles of marine sediments tend to have arsenic-rich content than coarser crystalline grains in general.

At an arsenic hot-spot, sulfide solid phases such as arsenic rich pyrite or arsenopyrite, are not always found. Although amorphous Fe dissolution is confirmed to play an important role in the release of arsenic, selective dissolution extractions indicate that adsorption of arsenic on carbonates and micas may also be an important component of arsenic cycling in the sediment (Charlet, 2007).

Causes and mechanism of arsenic contamination in groundwater is not clearly known, however, natural geological and geochemistry changes are presumed to be the primary reason for arsenic contamination.

① Arsenic rich beds, marine sediments, were eroded and transported by Kali Gandaki River from the specific parts of the Himalayas and gradually deposited along streams and ponds in Terai

② These arsenic bearing sediments occurred and partly formed the upstream or the downstream aquifer components

③ Arsenic rich pyrite or arsenopyrite etc. in upstream aquifers may release arsenic into downstream groundwater. Arsenic containing aquifer sediments adsorb and release arsenic to the groundwater influenced by redox potentials and pH etc.

④ Geochemistry plays a vital role in the release of arsenic to groundwater and its subsequent transport (Carruthers, et al. 2003)

⑤ The difference in mobility between sediments (aquifer) and groundwater makes complicated mechanisms

5-4. Future Issues

Many strategies were applied for securing safe drinking water in the world. For example, the aquifer storage recovery (ASR) systems to store

safe potable water are in use in South Florid. At a few sites however, interactions among native water, recharge water, and aquifer lithologies can affect water-quality and arsenic mobilization has been identified at several ASR systems located in west-central and southwest Florida (Arthur et al., 2001; Arthur et al., 2002; and Mirecki et al., 2005). Most arsenic contamination of drinking water in Parasi exceeded the WHO drinking water guideline of 10 μg/L. In Parasi arsenic contamination often occurs between 5 m to 50 m deep aquifers in general, therefore, deeper tubu-wells were newly constructed but later arsenic contamination gradually occurred in most cases. Also, rain water harvesting is popular especially in Kathmandu area as we surveyed. One of the most cost-effective methods would be arsenic filters. At Parasi (Atharahati) we tested both raw and filtered groundwater (Table 5). However, local base risk-communications and education are needed in advance.

In our next field study in Nepal we will consider followings:

① More detailed underground information including aquifer sediments, redox condition, and well construction.

② Sampling water; take samples after at least five minutes pumping-out to get fresh water from tubu-wells.

③ Identify more detailed location utilizing GPS

④ Interviewing local people to find out reasonable solutions

6. Summary of Findings

6-1. Value of pH

The sampled water at Lukla and Jomsom, both located in the Mountain region in Nepal, indicated acid pH (<6.7) and alkaline pH (8.0), respectively. The acid and alkaline nature will be influenced by the local lithology and its components. Two distinct lithofacies may generate difference in water quality. Lukla area mainly consists of metamorphosed rocks such as granite, gneiss, mica, and marble, however, the geologic strata in Jomsom area has clay, fine sand, weathered sandstones, slate, and shale. In Upper Mustang, upstream Jomsom, ammonites and belemnites often occur in Jurassic limestone and the fossils indicate that the strata of Jomsom area are marine sediments. Even though adsorption by alkaline soils may mitigate arsenic leaching, arsenic were mobilized promotionally by the alkaline nature of the surface water (Kali Gandaki River) and local groundwater.

6-2. NH_4^+

Elevated NH_4^+ concentrations in drinking water in Kathmandu suggest that the water sources (rivers) are contaminated by agricultural pollutants including manure, fertilizer, and excreta of livestock or human. Samples taken from other parts of Nepal did not show any prominent NH_4^+ level.

6-3. Calcium, Magnesium, and Natrium

Jomsom locates in the upstream area and Jomsom and Pokhara are in the same drainage basin. It means that their headwaters and the upstream areas are generating same minerals containing rich Ca^{2+} into the river water. We confirmed that about 80% of all chemical elements was Ca^{2+} in the water sampled in both areas. Geochemical compositions of sediments in both areas are basically similar

The weight percentages of Na^+(30%) and

Ca^{2+}(40%) in the sampled water at Manakamana and Kathmandu are similar as shown in Fig. 5. This may be partly because the headwater lithology is similar. Water characteristics of Parasi and Bharatpur also are similar each other, although the factor concentrations are different. The content (component) by percentage of sampled water at Parasi and Bharatpur was considered to bear a striking resemblance.

Concentration levels of Mg^{2+} and Ca^{2+} at Parasi and Lumbini are higher than other observation areas.

6-4. Water Hardness

High levels of Mg^{2+} and Ca^{2+} concentrations in groundwater at Parasi and Lumbini suggested that water quality is as bad as the drinking water hardness permissible limit of 300 mg/L (Japanese standard). Arsenic and boron in water sampled at Parasi have the strongest correlation of 0.97 as shown in Fig.8. Also, Fe and As in sampled water have high correlation.

6-5. Other Parameters

The concentration of arsenic will vary based on the depth of the aquifers, geology, and groundwater flow. It is clear that aquifer lithologies can affect local water-quality. Additionally seasonal change should be considered. Arsenic concentration is slightly lower in monsoon, which may indicate the possibility of dilution due to recharging or other reasons (Maharjan et al., 2006).

Studying arsenic mobilization and sequestration requires complete water-quality data. As Mirecki (2005) reported, minimum analytical requirements that define a complete water-quality data set are major dissolved inorganic anions and cations, pH, carbonate alkalinity, and redox-sensitive species concentrations (total sulfide, arsenate and arsenite, dissolved ferric and ferrous iron).

7. Conclusion

The arsenic distribution in aquifers is mainly restricted within the Holocene alluvial plain, the lowland Terai. An arsenic hot-spot locates very randomly but probably according to the local geology with the lateral and vertical variability, such as sedimentary facies, remains of former meandering, north-dipping thrusts, and multiple folds.

In order to identify the source of arsenic we investigated water quality and geology in four areas in Nepal, Mountain, Hill, Siwalik, and Terai. The metamorphic rocks of the Himalayas will least contribute arsenic contaminations in Terai because they are crystalline mainly consisting of feldspar, quartz and marble. However, weathered marine sediments with fluvial and fluvio-glacial deposits are identified in Jomsom (Annapurna Mountain area) where arsenic rich minerals including arsenopyrite (FeAsS) and arsenic trioxide (As2O3) are generally considered to have been eroded and transported by Kali Gandaki River. Arsenic bearing minerals were deposited at the specific beds in Terai during early-mid Holocene sea level rise.

Arsenic is mobilized in local groundwater with the alkaline nature and can be easily removed and adsorbed in aquifer sediments influenced by pH and redox conditions and by iron related geochemistry. By our study positive correlations have been confirmed among the total concentrations of boron and Fe with arsenic in the groundwater of Parasi in Terai.

References

Arthur, J.D., Cowart, J.B., and Dabous, A.A., 2001, Florida aquifer storage and recovery geochemical study: Year three progress report, Open File Report 83, Florida Geological Survey, 46 p.

Arthur, J.D., Dabous, A.A., and Cowart, J.B., 2002, Mobilization of As and other trace elements during aquifer storage and recovery, southwest Florida, In: U.S. Geological Survey Artificial Recharge Workshop Proceedings, Sacramento CA, April 2–4, 2002, G.R. Aiken and E.L. Kuniansky (eds.), U.S. Geological Survey Open-File Report 02-89, pp. 47–50.

Atkins, P., Hassan, M., Dunn, C., 2007, Poisons, pragmatic governance and deliberative democracy: The arsenic crisis in Bangladesh, Geoforum 38 (1), pp. 155-170.

Bhattacharya, P., Tandukar, N., Neku, A., Valero, A.A., Mukherjee, A.B., and Jacks, G., 003, Geogenic arsenic in groundwaters from Terai Alluvial Plain of Nepal, Journal De Physique. IV : JP 107 (I), pp. 173-176.

Brikowski, T., Smith, L., and Shrestha, S., 2005, Electrical Resistivity Profiling to Delineate Low groundwater Arsenic Target Zones in the Terai, Nawalparasi, Nepal, 2005 Salt Lake City Annual Meeting (October 16–19, 2005) Paper No. 164-2, Geological Society of America Abstracts with Programs, Vol. 37, No. 7, 375 p.

Charlet, L., Chakraborty, S., Appelo, C.A.J., Roman-Ross, G., Nath, B., Ansari, A.A., Lanson, M., and Mallik, S.B., 2007, Chemodynamics of an arsenic "hotspot" in a West Bengal aquifer: A field and reactive transport modeling study, 2007, Applied Geochemistry, 22 (7), pp. 1273-1292.

Chernicoff, S. and Whitney, D., 2002, Geology 3rd edition, Houghton Mifflin Company USA, pp. 434-465.

CIA (USA), 2007, CIA- The World Fact Book, Central Intelligence Agency U.S.A., Guide to Country Profiles, Nepal, last updated December 13, 2007, https://www.cia.gov/library/publications/the-world-factbook/docs/profileguide.html.

Carruthers, A.L., Wright, K., Burgess W.G., and Valsami-Jones, E., 2003, A Combined Experimental and Modeling Study of Arsenic Sorption on Goethite, Proc. 7th Intern. Conf. on the Biogeochem. of Trace Elements; Uppsala, 66 p.

Friedenreich, O.R., Slind, O.L., Pradhan, U.M.S., and Shrestha, R.B., 1994, Canadian Journal of Exploration Geophysics Vol.30, No.2, pp. 103-114.

Gurung, J.K., Ishiga, H., and Khadka, 2005, Geological and geochemical examination of arsenic contamination in groundwater in the Holocene Terai Basin, Nepal, Environmental Geology, Vol.49, pp. 98-113.

Maharjan M, Shrestha RR, Ahmad SA, Watanabe C, and Ohtsuka R., 2006, Prevalence of arsenicosis in Terai, Nepal, Journal of Health, Population and Nutrition, Volume 24, Issue 2, June 2006, pp. 246-252.

Maharjan M, Watanabe C., Ahmad, A., and

Ohtsuka R., 2005, Arsenic contamination in drinking water and skin manifestations in lowland Nepal: The first community-based survey, Am. J. Trop. Med. Hyg., pp. 1-3.

Maharjan M., 2006, Arsenic contamination in groundwater resources in Kathmandu Valley. International Symposium on Southeast Asian Water Environment, Vol.4, pp. 277-282.

Mirecki, E., 2005, As mobilization and sequestration during successive aquifer storage recovery (ASR) cycle tests in the carbonate Upper Floridan aquifer, South Florida, ISMAR 2005, 5th International Symposium, June 2005, Berlin German, pp. 304-310.

Miller, S.R. and Slingerland, R.L., 2006, Topographic advection on fault-bend folds: Inheritance of valley positions and the formation of wind gaps, Geology, Volume 34, Issue 9, September 2006, pp. 769-772.

Mohan, D. and Pittman Jr., 2007, Arsenic removal from water/wastewater using adsorbents-A critical review. Journal of Hazardous Materials, 142 (1-2), pp. 1-53.

Murcott S. and Lukacs, H., 2002, Household Water Treatment in Nepal, the MIT Civil and Environmental Engineering Department, www.com.washington.edu/ict4d/upload/20060301.

Pal, T., Mukherjee, P.K., and Sengupta, S., 2002, Nature of arsenic pollutants in groundwater of Bengal basin - A case study from Baruipur area, West Bengal, India. Current Science 82 (5), pp. 554-561.

Shrestha, A. B., Wake, C. P., Mayewski, P.A., and Dibb, J.E., 1999, Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971-94. Journal of Climate, 12 (9), pp. 2775-2786.

Smedley, P. L. and Kinniburgh, D. G., 2002, A review of the source, behaviour and distribution of arsenic in natural waters, Applied Geochemistry, Volume 17, Issue 5, May 2002, pp. 517-568.

Tamrakar, N.K., Yokota, S., and Osaka, O., 2002, A toppled structure with sliding in the Siwalik Hills, midwestern Nepal. Engineering Geology, 64 (4), pp. 339-350.

Tamrakar, N.K., Yokota, S., and Shrestha, S.D., 2007, Relationships among mechanical, physical and petrographic properties of Siwalik sandstones, Central Nepal Sub-Himalayas, Engineering Geology, Volume 90, Issue 3-4, 27 March 2007, pp. 105-123.

UNICEF, 2006, 'Nepal a world leader in boosting child survival, despite conflict', News Note on September 18, 2006, KATHMANDU, http://www.unicef.org/media/media_35949.html.

Upreti, B. N., 2000, An overview of the stratigraphy and tectonics of the Nepal Himalaya, Department of Geology, Tri-Chandra Campus, Tribhuvan University, Ghantaghar, Kathmandu, Nepal. Journal of Asian Earth Sciences, Vol.17, pp. 577-606.

Williams V. S., Breit, G. N., Whitney, J., and Yount, J. C., 2004, Investigations on the relation of arsenic-bearing sediments to arsenic contaminated groundwater beneath the plains of Nepal, Denver Annual Meeting (November 7–10, 2004) Paper No. 242-5, Geological Society of America Abstracts with Programs, Vol. 36, No. 5, 5 p.

ネパールにおける高度帯別水質特性およびテライ低地の地下水ヒ素汚染

The Drinking Water Quality in Four Physiograhic Regions of Nepal and Arsenic Contaminated Groundwater in Terai, Lowland Nepal

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ネパールの地形は、南部の標高 150m 以下のテライ、150～300m のシワリク、 300～2,500m のヒル/ミドルマウンテン、2,500m 以上のハイマウンテン等の高度帯に大別され、地質構造にも大きな特徴が見られる。

そこで 2007 年 8 月から 9 月に、標高 3,000m 以下のこれらの地帯を代表する 4 つの地域(1)を選定し、飲料水の水質調査を実施し、その概要を把握した。また、ヒ素汚染が報告されるテライ(Parasi)においては、地下水のヒ素汚染の実態について調査した。

(1) 飲料水水質調査地点

ハイマウンテン：Lukla (2,840m), Jomsom(2,710)
ﾋﾙ / ﾐﾄﾞﾙﾏｳﾝﾃﾝ：Kathmandu(1,300m), Pokhara(820m), Manakamana(1,300m)
シ ワ リ ク：Bharatpur(190 m)
テ ラ イ：Parasi(110m), Lumbini(100 m)

(2) ヒ素汚染調査地域

テ ラ イ：Parasi(110 m)

その結果得られた知見は,次の通りである。

(1) ハイマウンテンの Lukla では、pH6 台後半の値を示すが、同じﾊｲﾏｳﾝﾃﾝの Jomsom では pH8 を示す。これは、地層の違いによるものと考えられる。
(2) Kathmandu だけが NH_4^+を高濃度で検出した。これは、河川の人為的汚濁が原因であると考えられる。
(3) タライの沖積地帯に位置する Parasi、Lunbini では、他地域と比較して、Mg^{2+}、Ca^{2+} が高濃度に検出される。
(4) Jomsom は、Pokhara の上流に位置し、上流には海成堆積層が存在する。水源が共通しているため、ともに Ca^{2+} が 80%近くを占める。
(5) 同じ高度帯に隣接する Manakamana と Kathmandu は、地質構造が類似しているため、Na^+(30%超)、Ca^{2+}（40%前後）の比率が類似する。
(6) Parasi と Bharatpur は、各種成分濃度に関しては，後者が前者の約 1/4 と大きな違いはあるが、各種成分の濃度比は非常に類似している。
(7) Parasi、Lunbini の全硬度は、日本の水道水基準値（300mg/L）に近い値を示す。
(8) Parasi の As と B は、高い相関(r=0.97)を示す。
(9) Parasi においては，ヒ素の高濃度値が局所的に分布する。
(10) 高濃度ヒ素の局所的分布の原因としては、地下の帯水層の深さ・地質（粘土・砂・礫）構造などが複雑に入り組んでいるためと推測される。タライ沖積低地に位置する Parasi では地下水のヒ素汚染が不規則に分布することを確認した。その分析には、帯水層の地質状況の調査が重要である。特に造山運動による褶曲や衝上断層による間接的な影響や地下に存在する蛇行跡などが帯水層のメカニズムを複雑化している。さらに、ヒ素の地下水への溶出と帯水層中の移動に関して、ヒ素の広域汚染源、ヒ素含有岩石・砕屑物、海成堆積物、河川と風化の影響、地下水中の化学物質（特に鉄化合物や硫化物など)、pH、酸化還元電位なども大きく関与すると考えられる。