Journal of Nepal Geological Society, 2004, Vol. 30, pp. 115–122

Geological risk management*

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ABSTRACT

Geological risk management depends on the understanding of the underlying geological processes and their control on various geohazards. The significant responsibilities are post-crisis analysis with scenario formulation to develop strategies to mitigate the impact of future events and preparation of coordinated risk assessments for regions vulnerable to natural hazards. The evaluations are essential for developing hazard-resistant structures, building codes, better land use planning, hazard minimising policy, and emergency response plans. Two vital geological hazard scenarios, such as earthquake and arsenic contamination in groundwater in the Ganges–Brahmaputra–Meghna delta of Bangladesh, are elaborated as case studies. A complete cycle of seismic hazard assessment to seismic risk management is proposed. An earthquake prediction to risk management mechanism is identified together with the coordinated professional efforts for seismic risk assessment. The geological processes responsible for arsenic contamination in groundwater are pointed out and the role of geology in managing various geohazards is highlighted.

INTRODUCTION

Geological risk management depends essentially on the proper determination and assessment of geological hazards. It is of prime importance to know the types of hazards that might occur in the geological setting. The understanding of the underlying geological processes and controls of various geohazards leads to better risk management for minimising the loss of lives and property. Geohazards are unpreventable natural events. They bear the potentiality to expose population to the risk and may damage or destroy property, infrastructure, agricultural or other developed lands, and degrade the environment.

The study of geohazards includes long-term monitoring and forecasting of a disaster, short-term prediction, real-time monitoring, and communication with civil authorities and others during a crisis. Other significant responsibilities are post-crisis analysis with scenario formulation to develop strategies to mitigate the impact of future events and preparation of a risk management plan.

The geological risk may be grouped into geophysical risk, geochemical risk, and bio-geological risk. Geophysical risk is attributed mostly to earthquake, ground instability, liquefaction, rock slide, rock fall, land subsidence, and debris flow. Geochemical risk is associated with sediment pollution, ground- and surface water pollution, solute transport, and saline water entrapment and intrusion. Bio-geological risk is attributed to biogenic gas pocket formation and bacteriological contamination.

The disposition of chemical, biological, radioactive, and toxic wastes is the most serious geo-environmental problem of the near future. The major concerns are with transport, burial, and monitoring. The aims are to transport the waste without spillage due to a mishap (natural or anthropogenic), to bury the waste without any leakage during the burial, and to monitor the burial site in a continuous fashion for any leakage after burial. Characterisation of environmental sites is mostly limited because of the financial constraints and complex interaction of physical, chemical, and biological processes. The geological hazards like earthquakes, landslide, land subsidence and release of toxic elements from geological materials in the groundwater, can influence the ability to control and isolate the geo-environmental sites over time.

Hazard evaluation is essential for developing resistant structures and sound land use practices. It is also important for policy making and formulation, and developing emergency response plans. The geological maps should be used by local officials, planners, and designers to develop and refine new building codes; design safer highways, bridges, buildings, and utilities; estimate the stability and landslide potential of hillsides; derive insurance rates for properties; set construction standards to help ensure the safety of waste-disposal facilities; and plan earthquake disaster mitigation practices and emergency response procedures.

This paper is focused mainly on two vital geological hazard scenarios, earthquake and arsenic contamination in

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*Keynote paper, Fourth Nepal Geological Congress groundwater in the Ganges–Brahmaputra–Meghna (GBM) delta of Bangladesh.

EARTHQUAKE SCENARIO IN BANGLADESH

Earthquake is one of the major natural hazards threatening life, property, and economic well-being in many nations. Death tolls from major events could be sighted as 255,000 in Tangshan, China in 1976 and 10,000 in Mexico City in 1985. The economic loss in the 1995 Kobe, Japan, earthquake was more than US$100 billion. Nations striving for full economic development may find the investments and progress of decades wiped out in a few minutes.

Various tectonic processes can be related to the dynamic interaction between the lithospheric plates. The four principal modes of interaction between plates are subduction, extrusion, transcursion, and accretion (Lomnitz 1974).

The earthquakes have been associated with the internal stress build-up in the earth. The immediate cause of earthquakes is elastic rebound in rocks. The elastic rebound takes place along fault surfaces both in vertical and horizontal directions. The nature and direction of movement along a particular fault surface is determined by the focal mechanism solution. Earthquake events are defined by their location (latitude, longitude, and depth), time of occurrence, and energy released. The latter is difficult and cumbersome to determine. The Richter scale uses the maximum surface wave amplitude in the seismogram and the difference in the arrival times of primary (P) and secondary (S) waves for determining the magnitude (M). The magnitude is related approximately to the logarithm of energy (E). The strength of shaking at the earth's surface is usually reported on a non-instrumental scale, called the Modified Mercalli Intensity (MMI) scale. The relationship between the magnitude M, the intensity I, and the focal depth R (km) is given by the following equation (Esteva and Rosenblueth 1964).

$$I = 8.16 + 1.45\,M - 2.46\log_{10}R$$

Instead of the intensity I, the peak ground motion Y may directly be measured. Depending on the type of instrument, Y may be given in terms of displacement, velocity, or acceleration.

Since, it is impossible to obtain an infinitely long history of earthquake occurrence in a region to establish its true nature, the normal procedure is to employ data over a restricted period using various statistical models. Two common statistical methods viz., the magnitude-frequency relation and the extreme value theory are in use in the field of seismology to ascertain the level of seismicity of a region in terms of the return period and the probability of occurrence of a large earthquake.

A study of cumulative strain accumulation and release over a given period offers a useful means of comparing the earthquake activities of different regions and of the same region over different periods. It is possible to illustrate the relative strain level obtained in a region at different times by means of a strain accumulation and relaxation curve. The rate of strain release per unit area per unit time can reveal some striking trends of seismic activity in close parallelism with the tectonic features of a given region.

If we imagine a complete cycle from seismic hazard assessment to seismic risk management, the seismic risk is the cumulative effect of seismic hazard, site characteristics, and vulnerability.

$$\text{Seismic risk} = \text{seismic hazard} + \text{site effects} + \text{vulnerability}$$

Where seismic hazard is the probability of the ground motion, site effects is the amplification factor due to soil and topography, vulnerability means the building type and age, population density, land use, value, and time and date. All these, when collectively applied to seismic risk, imply the probability of damage and losses.

The preferential responsibilities of the various professionals with respect to the components of seismic risk management may be looked as per Table 1.

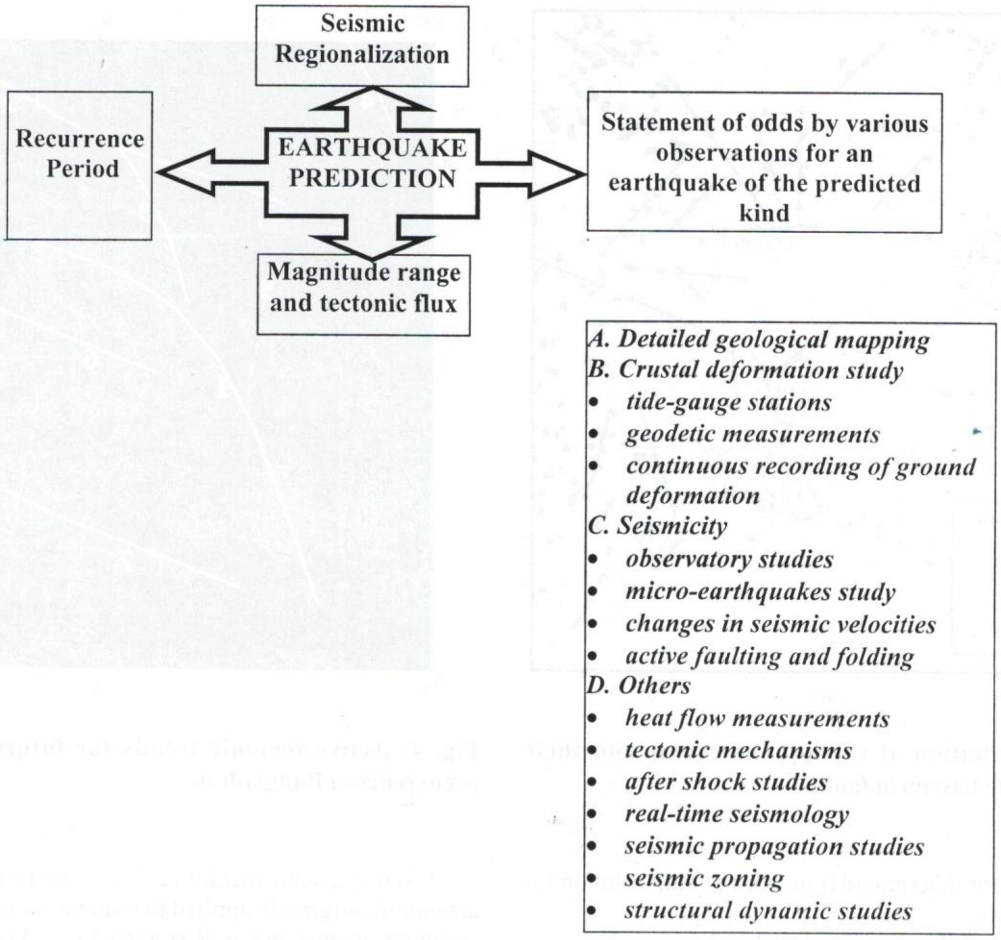
The essential elements are required for a valid earthquake prediction. The organogram (Fig. 1) is self-explanatory (Khan et. al. 2001). The earthquake risk management approach is recommended according to the organogram (Fig. 2).

Although Bangladesh is extremely vulnerable to seismic activity, the nature and the level of seismic activity is poorly defined. The main constraints are the earthquake observation and monitoring facilities.

Active faults have been identified based on the distribution of earthquake events and their correlation with basement faults (Fig. 3). Various active tectonic trends have also been identified in Bangladesh (Hoque and Khan 2001) (Fig. 4). The active faults exhibit strike-slip and thrust movements (Khan and Chouhan 1996). However, there are some regions in the Bengal basin characterised by vertical

Table 1: Seismic risk management components

Components	Preferential responsibilities
Seismic Hazard	Seismologist Geologist Engineer
Site Effects	Geologist Engineer Seismologist
Vulnerability	Engineer Land Use Geographer
Seismic Risk	Seismologist, Geologist, Engineer, and Land Use Geographer in combination.



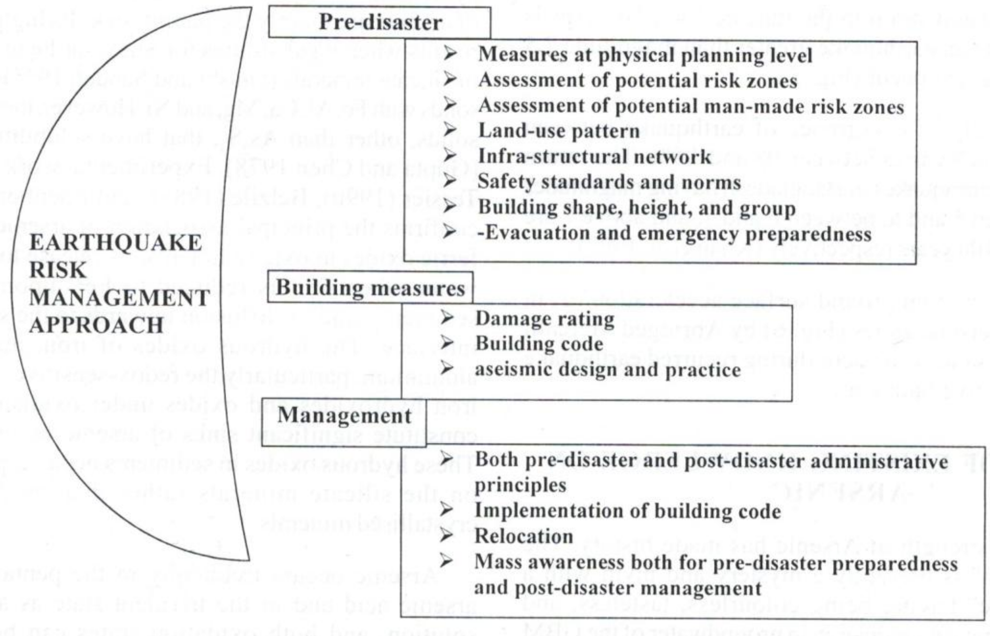
A. Detailed geological mapping

B. Crustal deformation study
- *tide-gauge stations*
- *geodetic measurements*
- *continuous recording of ground deformation*

C. Seismicity
- *observatory studies*
- *micro-earthquakes study*
- *changes in seismic velocities*
- *active faulting and folding*

D. Others
- *heat flow measurements*
- *tectonic mechanisms*
- *after shock studies*
- *real-time seismology*
- *seismic propagation studies*
- *seismic zoning*
- *structural dynamic studies*

Fig. 1: Essential elements required for earthquake prediction



Pre-disaster
- ➢ Measures at physical planning level
- ➢ Assessment of potential risk zones
- ➢ Assessment of potential man-made risk zones
- ➢ Land-use pattern
- ➢ Infra-structural network
- ➢ Safety standards and norms
- ➢ Building shape, height, and group
- ➢ -Evacuation and emergency preparedness

Building measures
- ➢ Damage rating
- ➢ Building code
- ➢ aseismic design and practice

Management
- ➢ Both pre-disaster and post-disaster administrative principles
- ➢ Implementation of building code
- ➢ Relocation
- ➢ Mass awareness both for pre-disaster preparedness and post-disaster management

Fig. 2: Approach of earthquake risk management

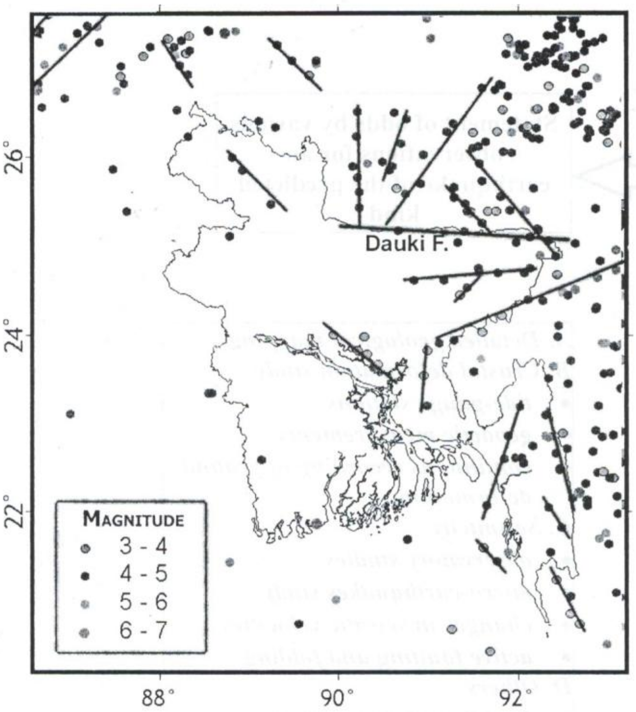


Fig. 3: Distribution of earthquake events and their correlation with basement faults

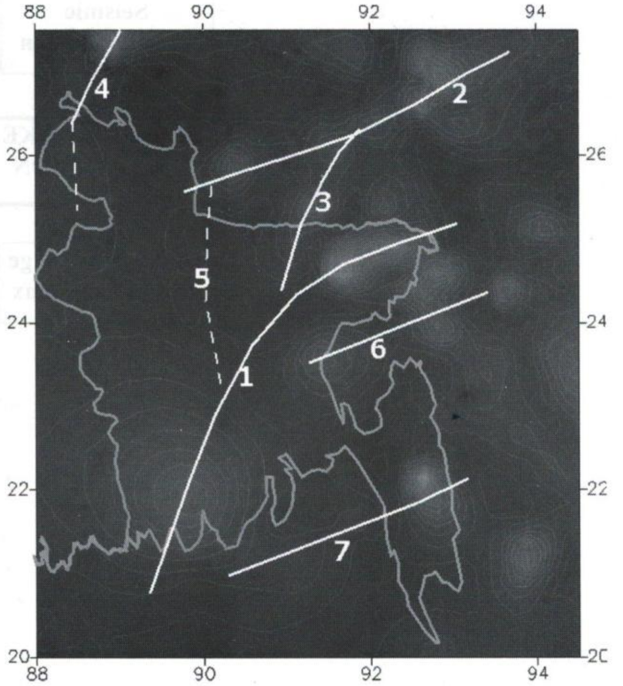


Fig. 4: Active tectonic trends for future earthquake occurrence in Bangladesh

fault movement as determined from normal fault solution for couple of events.

A quantitative assessment has been made and it is found that the annual rate of strain accumulation corresponds to M = 6.5 is 4.5 x 10^{21} ergs. The study further suggests that the present accumulated strain to the tune of 3.4 x 10^{23} ergs is likely to generate an earthquake greater than magnitude 7.5 should a single event occur (Fig. 5).

The probability of occurrence of earthquake between magnitudes 6 and 8 varies between 98 and 99%. The return period of major earthquakes in Bangladesh having magnitudes below 5, between 5 and 6, between 6 and 7, and above 7 are 1.5, 12, 50, and 100 years respectively (Khan et al. 1998).

Proposed maximum ground surface acceleration (g) in the respective seismic zones (Fig. 6) by Abridged Mercalli Intensity Scale is likely to occur during recurred earthquake located in the active fault zone.

REVIEW OF EXISTING KNOWLEDGE ON ARSENIC

The killing strength of Arsenic has made history. The "king of poison" is presently a mystery and myth with a synonym "toxic" having being colourless, tasteless, and odourless. Arsenic contamination in groundwater of the GBM delta is a unique and complex problem.

Arsenic, a semi-metal that has come from Greek name arsenikon, originally applied to mineral orpiment. The most common arsenic ore is Realgar (AsS). Arsenopyrite and pyrite are known as a paragenetic pair. The natural occurrence of arsenic in soils and rocks has been reviewed by Reidel and Eikmann (1986) and Tanaka (1988). The sources of arsenic are mainly the parent rock. Its high concentration results when it substitutes for Si, Al, or Fe in crystal lattices of silicate minerals (Onishi and Sandell 1955). Arsenic forms solids with Fe, Al, Ca, Mg, and Ni. However, there are no arsenic solids, other than As_2S_3, that have solubilities >0.05 mg/l (Gupta and Chen 1978). Experimental work by Belzile and Tessier (1990), Belzile (1988), and Edenborn et al. (1986) confirms the principal association of arsenic with hydrous ferric oxides in oxic sediments, its release to the interstitial water when Fe^{3+} is reduced to Fe^{2+} upon burial of the sediments, and its diffusion upwards to the sediment-water interface. The hydrous oxides of iron, manganese, and aluminium, particularly the redox-sensitive manganese and iron hydroxides and oxides under oxidising conditions, constitute significant sinks of arsenic in aquatic systems. These hydrous oxides in sediments occur as partial coatings on the silicate minerals rather than as discrete, well-crystallised minerals.

Arsenic occurs frequently in the pentavalent state as arsenic acid and in the trivalent state as arsenite in soil solution, and both oxidation states can be subjected to chemically and microbiologically mediated oxidation,

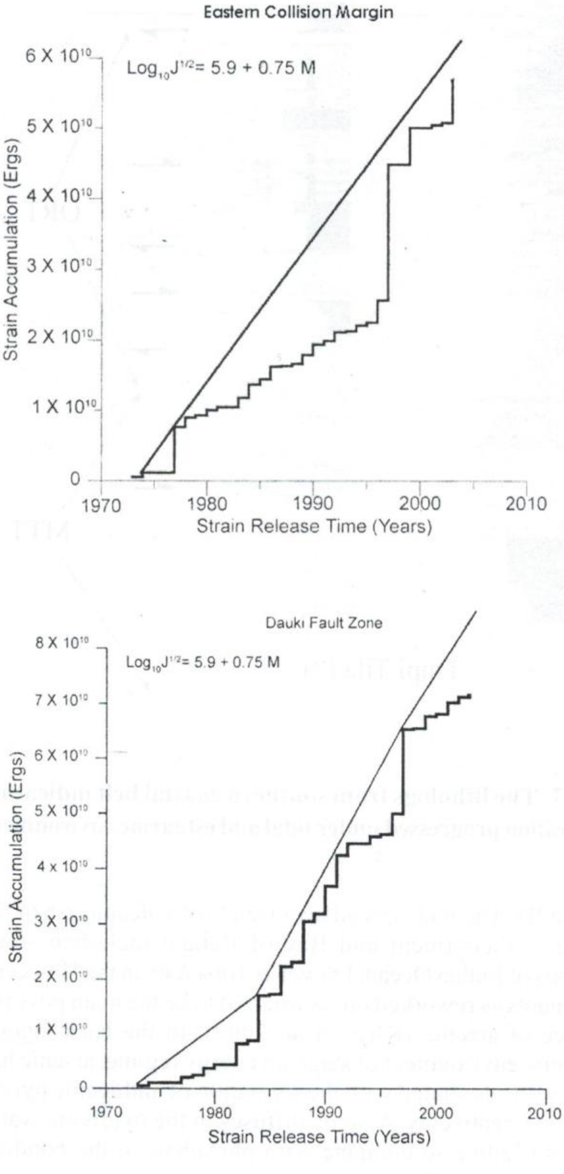


Fig. 5: Annual rate of strain accumulation pattern in Bangladesh

reduction, and methylation reactions (Walsh and Keeney 1975). The biological availability and physiological and toxicological effects of arsenic depend on its chemical form and As^{3+} is much more toxic, more soluble, and more mobile than As^{5+}(Webb 1966). The oxidation and reduction of arsenic in soil is related to the population of microorganisms (Green 1918).

Arsenite (As^{3+}), the reduced state of inorganic arsenic, is a toxic pollutant. It is more toxic, soluble, and mobile than the oxidised state of inorganic arsenic, Arsenate (As^{5+}). Arsenate can be sorbed onto clays, especially montmorillonite [$(OH)_4Al_4Si_8O_{20}.nH_2O$] and kaolinite [$(OH)_8Al_4Si_4O_{10}$]. Arsenic enters in groundwater both as As^{3+} and As^{5+} either from parent minerals or from sediments those adsorb arsenic. Arsenic is strongly adsorbed in clay and shale. Sorption of arsenate is increased with increasing clay particles.

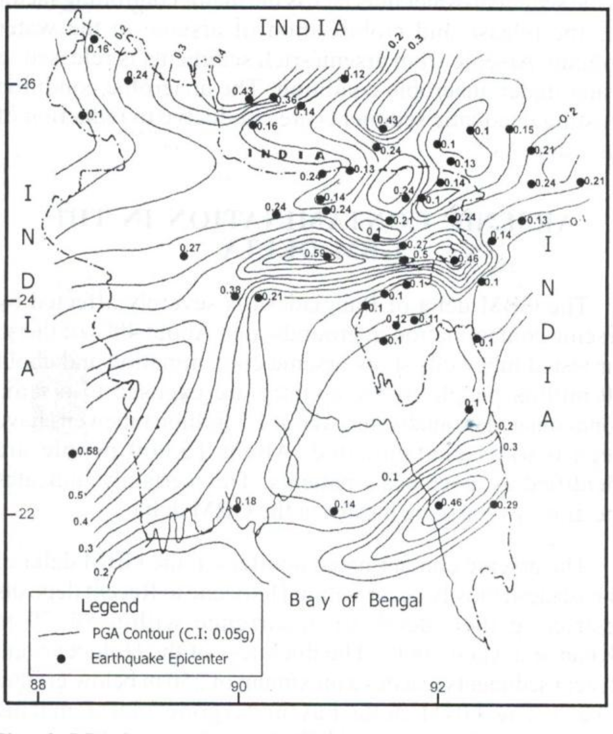


Fig. 6: Maximum ground surface acceleration (g) in the respective seismic zones of Bangladesh

The genesis of arsenic-bearing minerals begins at the bottom of lakes and oceans (Schaufelberger 1994). Here, arsenic is collected from all possible sources; biological and anthropogenic, crustal weathering, deeper origins through hot springs, and geothermal systems, from active ocean ridges by upwelling of magma, and through the leaching of basalts. Arsenic minerals occur in hydrothermal veins, in sulphide veins, in calcareous shales and marbles in close proximity to a dyke of basic intrusive rocks. Two processes derive arsenic in the sediments: a) as denuded, fragmented, weathered, and eroded particles of parent arsenic-bearing minerals from the source regions, b) as adsorption of arsenic in the sediment grains coating from arsenic-rich aqueous solution. Acid mine drainage from largely coal and to some extent gold mining often contains large concentrations of both iron and arsenic due to oxidation of pyrite.

The microbs including bacteria, fungi, and algae can make physical and chemical changes in the environment. Exposure of sediments to oxygen provides conditions suitable for chemolithotrophic bacteria to oxidise the sulphides, releasing iron and any arsenic associated with sulphides. Arsenic is released from sediments and its mobility in groundwater is due to acid formation wherein the principal role is played by chemolithotrophic bacteria (Khan et al. 2003). Redox potential in the sediment-water interface is the major controlling factor for the release and mobilisation of arsenic in the water column. Arsenic from arsenic-rich sediments is released to water under anaerobic condition. The anaerobic condition existing in aquatic sediments are conducive to reduction of As^{5+} into As^{3+}.

ARSENIC CONTAMINATION IN THE GBM DELTA

The GBM delta of Bangladesh is severely affected by arsenic contamination in groundwater. About 40% of the so far tested tubewells show arsenic contamination and about 50 million people of the country are exposed to arsenic contaminated groundwater. About 1.3 million tubewells have been marked contaminated. About 10,000 people are identified as arsenicosis patients. This certainly indicates the gravity of arsenic hazard in the GBM delta.

The arsenic contaminated aquifers in the GBM delta of Bangladesh mostly occur within Holocene to Recent deposits restricting their depth of occurrence within 50–70 m (Khan and Alam 2000). The thickness of the Holocene and Recent sediments reaches a maximum of 250 m below ground level. The GBM delta has undergone major marine transgression during the mid-Holocene from 6 to 8 thousand years ago (Khan et al. 2000). The marine transgression progressed along well-defined Holocene depressions viz., the Ganges–Mahananda depression, Jamuna depression and Meghna depression (Khan et al. 2000). Both sediments and groundwater in these depressions are significantly contaminated by arsenic. While the aquifers located in the exposed Pleistocene deposits viz., the Barind Tract, the Modhupur Tract, and the Eastern Folded Belt are free from arsenic contamination.

Lithologs from boreholes signify that the Holocene aquifers are characterised by fining-upward sequence intercalated with channel-fill and overbank deposits with frequent channel migration. The lithologs from southern coastal belt suggest that the deposition progressed under tidal and estuarine environments (Fig. 7). A characteristic feature is the development of pronounced surface coatings on the detrital grains including quartz and feldspar. The coatings are dark brown to black in colour, generally thin but often thick to very thick. The grain coatings are mainly of FeOOH and MnOOH, and SEM-EDEX analysis provides evidence of arsenic in the coatings (Fig. 8). Highly calcareous thick clay layer of about 110 m lying just below the arsenic-contaminated aquifer zone has been encountered in some places. The matrix of the aquifer sediments is also calcareous. This clay is basically aragonite mud, which is undergoing the process of micro-crystallisation to dolomite. The dolomitisation process in turn spells out water-soluble arsenic into the overlying aquifers.

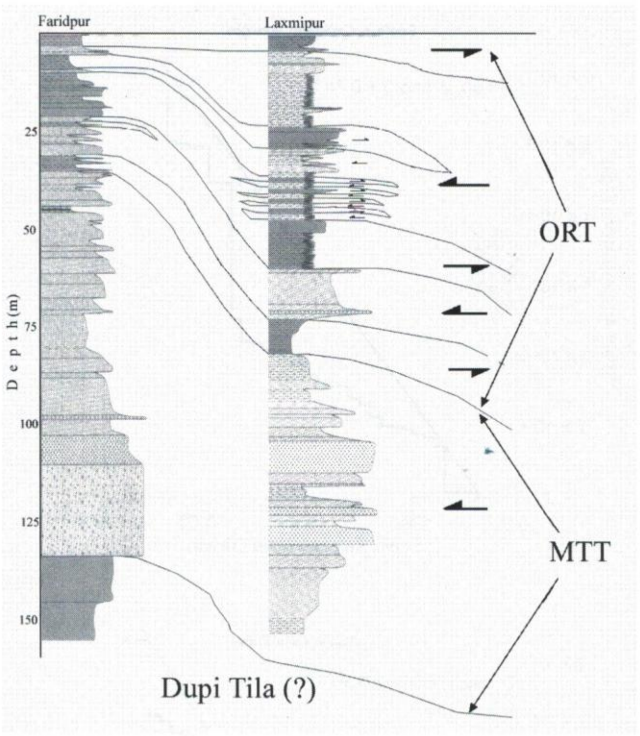


Fig. 7: The lithologs from southern coastal belt indicating deposition progressed under tidal and estuarine environment

Arsenic-rich seawater has been entrapped in the sediments of Holocene deposits due to marine transgression by adsorption in the grain coatings of mostly FeOOH and MnOOH. The widespread occurrence of volcanic ash in the Indian subcontinent and Bay of Bengal including some regions of Indian Ocean, known as Toba Ash, in the Holocene sediments as reworked one is inferred to be the main possible source of arsenic (Khan et al. 2000). In the back lagoon swampy environment of stagnant energy regime, arsenic has also been associated with the formation of authigenic pyrite, peat and peaty clay. Arsenic diffuses in the overlying water column failing to compete with phosphate at the bonding sites.

The release of arsenic and its mobility in the groundwater from these sediments is due to the acid formation, mainly by chemolithotrophic bacteria. The presence of a higher percentage of organic matter, Fe, and Al oxides enhances the oxidation rate, which in turn reduces the aquifers and creates the environment for arsenic release and solubility (Khan et al. 2003).

The issue of water use and arsenic-free water supply eventually cropped up. The debate mainly focused on whether or not the utilisation of groundwater should be stopped. Switchover to surface water instead of tapping groundwater from deeper aquifers is a sustainable option. Filtering of arsenic contaminated groundwater has also been thought by some agencies. Hence, the options for arsenic-free water supply are of three-fold: 1. switching over to surface water, 2. tapping the deeper aquifers, and 3. removal of arsenic

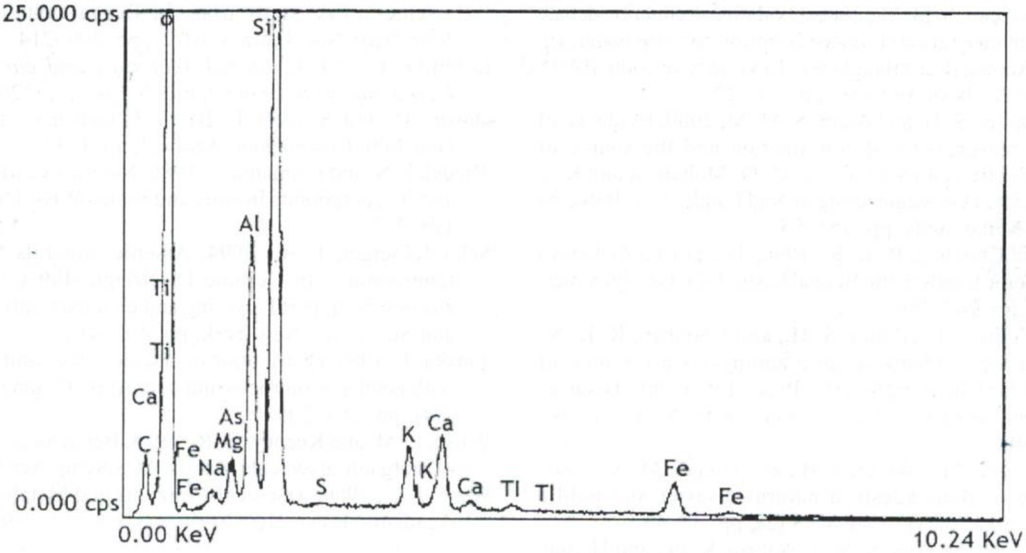


Fig. 8: SEM-EDEX analysis provides evidence of arsenic in the grain coatings

from contaminated groundwater. After a five-year-long debate, the consensus has largely been developed that our surface water resource is very limited and potential for anthropogenic contamination. Rainwater harvesting is not feasible due to a very short duration of rainy season and a long dry season. On the other hand, the arsenic-contaminated region being severely flood-prone, surface water management for safe drinking water is practically impossible. The removal of arsenic from contaminated water is also overruled due to its production and the problem of safe disposal of arsenic sludge. The only option is left then with the exploitation of deeper aquifers having proper clay barrier or sealing material below the arsenic-contaminated zones.

In order to achieve successfully the task of locating deeper pre-Holocene aquifers with overlying clay-bearer needs subsurface geological mapping. The field investigation and the research findings confirmed that the shallow zone of up to 70 m depth is acutely vulnerable to arsenic contamination, solute and pathogenic contamination from on-site sanitation, and other human and biological activities.

From a sample survey, it is found that 68% of the respondents are aware of the arsenic hazard and are in search of acceptable options, 93% opined in favour of tubewell water from safe aquifers, which they think is relatively easy, safe, and a continuous supply of drinking water. Similarly, 56% preferred community-based implementation of groundwater as safe water option and 42% wish to install safe water source privately. Further to the findings, 85% of the people are in favour of contributory participation for safe water supply.

CONCLUSIONS

Geology and geological processes are largely responsible for all geohazards like earthquake and groundwater contamination. Geological hazards cannot be prevented and their mitigation and achievement cannot be fulfilled ignoring geology.

A geohazard risk manager must have the knowledge of geology, geophysics, and geochemistry. It is the geologists who should carry the responsibilities in providing much better pre-disaster physical planning to the communities to safeguard their lives and property. It is also the geologists who should conduct evaluations following disasters to help minimise the impacts of future events and to help communities prepare better hazard assessments for the vulnerable regions. It is certain that geologists have much to contribute in geological risk management through investigation, policy making, and implementation for the benefit of the people, society, and nation.

REFERENCES

Belzile, N., 1988, The fate of arsenic in sediments of the laurentian Trough. Geochim. Cosmochim. Acta, v. 54, pp. 103–109.

Belzile, N. and Tessier, A., 1990, Interactions between arsenic and iron oxyhydroxides in lacustrine sediments. Geochim. Cosmochim. Acta, v. 54, pp.103–109.

Edenborn, H. M., Belzile, N., Mucci, A., Lebel, J., and Silverberg, N., 1986, Observations on the diagenetic behavior of arsenic in a deep coastal sediment. Biogeochemistry, v. 2, pp. 359–376.

Esteva, L. and Rosenblueth, E., 1964, Espectros de temblores a distancias moderadas y grandes. Bol. Soc. Mex. Ing. Sismica, v. 2, pp. 1–18.

Gupta, S. K. and Chen, K. Y., 1978, Arsenic removal by adsorption. Jour. Water Pollut. Control Fed., v. 50, pp. 493–506

Green, H. H, 1918, Description of a bacterium which oxidizes arsenite to arsenate, and of one which reduces arsenate to arsenite, isolated from a cattle dipping tank. S. Afr. Jour. Sci., v. 14, pp. 465–467.

Hoque, M. A. and Khan, A. A., 2001, Seismicity and seismotectonic regionalization of the Bengal basin, Bangladesh, Bang. Jour. Geol., v. 20, pp. 77–86.

Khan, A. A. and Alam, S. M. M., 2000, Oxidation-Reduction debate on arsenic in groundwater vis-a-vis option for safe water, In: M. Feroze Ahmed (Edt.) Bangladesh Environment 2000. BAPA Bangladesh Poribesh Andolon, pp. 210–221.

Khan, A. A., Akhter, S. H. and Alam, S. M. M, 2000, Evidence of Holocene transgression, dolomitization and the source of arsenic in the Bengal Delta, *In*: A. M. O. Mohamed and K. I. Al Hosani (edts.) Geoengineering in Arid Lands, A. A. Balkema Publ., The Netherlands, pp. 351–355.

Khan, A. A. and Chouhan, R. K. S., 1996, The crustal dynamics and the tectonic trends in the Bengal basin, Jour. Geodynamics, v. 22 (3/4), pp. 267–286.

Khan, A. A., Hoque, M., Akhter, S. H., and Chouhan, R. K. S., 1998, Multiple elements seismic zoning vis-a-vis state of seismic hazard in Bangladesh. Proc. Int. Conf. Disaster Management, Tezpur University, Guwahati, Assam, India., pp. 348–364.

Khan, A. A., Hoque, M., Akhter, S. H., and Hoque, M. A., 2001, Earthquake in Bangladesh: a natural disaster and public awareness, Jour. of NOAMI, v.18 (2), pp. 37–46.

Khan, A. A., Hoque, S., Huq, S. M. I., Kibria, K. Q., and Hoque, M. A., 2003, Evidence of bacterial activity in the release of arsenic- a case study from the Bengal delta of Bangladesh. Jour. Geol. Soc. India, v. 61(2), pp. 209–214.

Lomnitz, C., 1974, *Global Tectonics and earthquake Risk, Developments in Geotectonics* 5, Elsevier, 320p.

Onishi, H. and Sandell, E. B. 1955, Geochemistry of Arsenic. Geochim. Cosmochim. Acta v.7, pp. 1–33.

Riedel, F. N. and Eikmann, T., 1986, Natural occurrence of arsenic and its compounds in soils and rocks. Wiss. Umwelt 3–4, pp. 108–117.

Schaufelberger, F. A., 1994, Arsenic minerals formed at low temperatures In: Jerome O. Nriagu (Edt.), Arsenic in the environment, part I: cycling and characterization, John Wiley and Sons, Inc., New York, pp. 403–415.

Tanaka, T., 1988, Distribution of arsenic in the natural environment with emphasis on rocks and soil. Appl. Organomet. Chem., v. 2(4), pp. 283–295.

Walsh, L. M. and Keeney, D. R., 1975, Behavior and phytotoxicity of inorganic arsenicals in soils. ACS Symp. Ser. v. 7, pp. 35–52.

Webb, J. L., 1966, Arsenicals. Enzyme and Metabolic Inhibitors. Academic Press, New York, v. 3, pp. 595–790.