

Mapping and interpretation of field data for evaluation and mitigation of groundwater arsenic contamination in Bangladesh

S. Shams, P. Bhattacharya, S. Langaas, G. Jacks, K. M. Ahmed, E.-L. Thunkvist, D. Chen and A. Granlund

ABSTRACT

Problems of arsenic contamination have been reported from a large number of aquifers in various parts of the world. Especially in Bangladesh, the presence of arsenic in groundwater has been the major environmental health catastrophe that has affected the source of safe water not only for drinking but also for irrigation purposes. The unavailability and inaccessibility of data and dissemination of proper and rapid information has further reduced the accessibility to safe drinking water for nearly 95% of the population of the country. The development of solutions for the arsenic problem and the allocation of resources for mitigation are information-oriented activities. This paper focuses on the mapping and interpretation of field data (based on a case study area) through the application of GIS for presenting and assessing the scope of the arsenic problem in Bangladesh. The mapping and interpretation is done taking into consideration the geophysical characteristics, socio-economic conditions and socio-cultural behavior of the people living in the study area. The mapping and interpretation technique is aimed at assisting planners and policy makers at the district level to make an assessment about the extent and magnitude of the arsenic problem based on an estimation of the exposed population and the extent and severity of groundwater contamination. In addition, it will enable decision-makers to select possible options and give recommendations based on users' responses. The advantages of this interpretation technique are that the knowledge base is easy to build and any updated information or modifications can be quickly incorporated into the knowledge base.

Key words | arsenic, contamination, GIS, InstantTEA, mapping, mitigation option, tubewell

S. Shams (Corresponding author)
KTH-International Groundwater Arsenic
Research Group,
Department of Land and Water Resources
Engineering,
Royal Institute of Technology (KTH),
SE-100 44 Stockholm, Sweden
Present address: School of Mechanical,
Aerospace and Civil Engineering (MACE),
The University of Manchester,
Manchester M13 9PL, UK

P. Bhattacharya
S. Langaas
G. Jacks
E.-L. Thunkvist
Department of Land and Water
Resources Engineering,
Royal Institute of Technology,
SE-100 44 Stockholm, Sweden

K. M. Ahmed
Department of Geology,
University of Dhaka,
Dhaka-1000, Bangladesh

D. Chen
School of Mechanical, Aerospace and Civil
Engineering (MACE),
The University of Manchester,
Manchester M13 9PL, UK

A. Granlund
Department of Information and
Communication Technology,
Swedish International Development
Cooperation Agency (Sida),
SE-105 25 Stockholm, Sweden

INTRODUCTION

Arsenic contamination has been identified as a major problem in groundwater from a large number of aquifers in different parts of the world. Groundwater resources in countries like Argentina, Mexico, southwestern parts of the USA, Taiwan, Vietnam and northern China are affected with arsenic contamination. Arsenic concentrations ranging from 10–720 µg/L have been found in Carcarana River Basin and

concentrations ranging from 4–14 969 µg/L have been found in groundwater in the La Pampa and Santiago del Estero Provinces of Argentina (Nicolli *et al.* 1989, Smedley *et al.* 1998; Bejarano & Nordberg 2003; Claesson & Fagerberg 2003; Bundschuh *et al.* 2004; Bhattacharya *et al.* 2005). The Lagunera Region of north central Mexico, with an estimated population of 400 000, has identified arsenic concentrations

>50 $\mu\text{g/L}$ (Del Razo *et al.* 1990). Problems of arsenic have also been identified in aquifers of north-east Taiwan (Hsu *et al.* 1997). Preliminary results from Hanoi, Vietnam indicate that there is a significant arsenic problem in shallow tubewells in the city, particularly in the south (Berg *et al.* 2000). Arsenic occurrence has been found at high concentrations in excess of the Chinese national standard of 50 $\mu\text{g/L}$ in groundwater from Inner Mongolia as well as Xinjiang and Shanxi Provinces (Wang & Huang 1994; Niu *et al.* 1997). Arsenic associated with geothermal waters has been reported in several areas, including hot springs from parts of the USA, Japan, Chile, New Zealand and France (Welch *et al.* 1988; Criaud & Fouillac 1989). The most noteworthy occurrence has been identified in parts of West Bengal (India) and Bangladesh that exceed the WHO standard of 10 $\mu\text{g/L}$ (WHO 2001) as well as Bangladesh standard of 50 $\mu\text{g/L}$ (GOB 1997). However, several recent studies indicate that the severity of groundwater arsenic contamination in the Holocene Gangetic plains of Indian states of Bihar, Uttar Pradesh and Jharkhand is also as severe as in the Bengal Delta Plain in West Bengal and Bangladesh (Dhar *et al.* 1997; Chakraborti *et al.* 2004; Bhattacharjee *et al.* 2005). Arsenic contaminations have also been subsequently reported in groundwater from several countries of south Asia such as Nepal (Tandukar *et al.* 2005) and more cases are likely to be discovered (Chakraborti *et al.* 2004).

Since the 1970s, groundwater has been the major source of safe drinking water in Bangladesh. Groundwater abstracted from shallow aquifers at depths <60 m by hand-pumped tubewells has been widely accepted as safe water in rural areas for drinking purposes. Following the tremendous success in the provision of safe drinking water to nearly 95% of the population in Bangladesh through tubewells (BRAC 2000), the presence of arsenic in the groundwater from different parts of the country has emerged as a serious threat to public health. As many as 60–75 million people are currently exposed to the risk of severe arsenic poisoning (Mukherjee & Bhattacharya 2001; Ahmed *et al.* 2004). Water samples collected from the arsenic affected areas of the country revealed that 28% of the affected people had more than 100–1500% of normal levels of arsenic in their urine (normal level: 0.5–4 $\mu\text{g/L}$), 47% had 8–20% in their nails (normal level: 43–1080 $\mu\text{g/kg}$), and 98% had 100–15000% more than normal levels of arsenic in their skin (normal level: 466–896 $\mu\text{g/kg}$) (Arnold *et al.* 1990;

Samanta *et al.* 1999; Chowdhury 2000; Karim 2000; Marimuthu, 2001). The number of patients seriously affected by arsenic from drinking water has now risen to the thousands. Therefore an urgent approach is needed to encounter the problem of arsenic contamination.

Given the magnitude of the catastrophe, a resource-constrained nation like Bangladesh is now struggling to cope with the problem of arsenic contamination. The availability and accessibility of data and the dissemination of proper and rapid information has further limited the decision-makers in taking appropriate and reasonable actions.

The flow of information is a prerequisite for the proper understanding of any problem. Geographic Information Systems (GIS) and Expert Systems have often been very useful in handling information on environmental problems. Since measures of arsenic mitigation are based on rapid dissemination of information and promotion of awareness, development of interpretation techniques which give detailed scenarios of the arsenic crisis are likely to play a significant role in finding a sustainable solution.

A GIS is an information management system capable of providing spatial analysis for sorting, retrieving and manipulating geo-referenced computerized maps (Worboys 1996). A GIS provides a much-needed framework for approaching, supporting and making spatial decisions (Heywood *et al.* 1998) and is a potentially powerful tool for the manipulation and analysis of data. It has grown out of a number of other technologies and a variety of application fields, representing a meeting point between many different disciplines concerned with geographic locations (Martin 1996). A GIS enables decision-makers to answer complex questions more quickly and more accurately compared to those using paper maps. In contrast, Expert Systems are a specialized form of Artificial Intelligence. They are designed so as to replicate the problem-solving techniques of an expert in a narrow area of specialization, where reasoning is applied rather than calculation (Beerel 1987). There is never enough expertise to go around – certainly it is not always available at the right place and the right time. Portable computers loaded with in-depth knowledge of specific subjects can provide a decade's worth of knowledge for solving specific problems. The approach for the sustainable mitigation of the arsenic problem and the allocation of resources thus should depend on the activities based on the flow of information.

The present paper focuses on the development of a mapping and interpretation technique through the application of GIS for presenting and assessing the scope of the arsenic problem in Bangladesh. The study is based on the 'Chapai Nawabganj' district in northwestern Bangladesh, where arsenic was first detected in groundwater. The mapping and interpretation technique is designed to assist planners and policy makers at the district level in making an assessment about the extent and magnitude of the problem based on the estimated exposed population and degree of contamination. In addition, it will enable decision-makers to select possible options and give recommendations based on users' responses.

STUDY AREA

The mapping and interpretation technique was developed based on a case study area in Chatrajitpur Union of Shibganj thana in the village called Chatrajitpur of Chapai Nawabganj district in northwestern Bangladesh (Figure 1(a, b)). Chapai Nawabganj district is demarcated by the international border with the state of West Bengal, India in the west, Rajshahi district on the southeast and Noagaon district towards the northeast. The two major rivers, the Ganges and the Mahananda, along with tributaries such as the Pagla, Purnabha and Tangan, flow through the district of Chapai Nawabganj. It has an area of 1702 km² with a population of 1396 000. The district has 5 thana: Nawabganj Sadar, Shibganj, Nachole, Bholarhat and Gomastapur. Arsenic patients were first detected in Chapai Nawabganj district and the survey carried out by BGS identified some of the areas of the district as 'hot spots' with high concentrations of arsenic (BGS & DPHE 2001). The knowledge base of the interpretation technique was developed based on the survey carried out on a random basis in 67 households out of an estimated 163 households in Chatrajitpur village of Shibganj Thana.

GEOLOGY AND HYDROGEOLOGY

The surface geology of the study area is comprised of mainly alluvial sand of the active Ganges floodplain in the south and alluvial silt and clay in the north. The northeastern part of the fault-bounded Barind Tract has been uplifted by some 50 m

relative to the neighboring Holocene alluvium (Ahmed & Burgess 1995). Alluvial sediments comprising sand and silt, and occasional lenses of clay, characterize the aquifers.

Groundwater is the most important source of water supply in the study area. The aquifers supplying the major drinking water needs of the districts are placed at depths between 10–54 m below ground surface. The hydrographs for the district Chapai Nawabganj, based on observations from the national piezometric network, indicate a large seasonal fluctuation, with water levels ranging from around 1 m below ground level at the end of the monsoon period to around 7 m below ground level during the dry season (BGS & DPHE 2001). Groundwater levels for dug wells showed very similar responses to the piezometers during the monitoring period, with fluctuations of around 6 m. In the shallow aquifer, groundwater flows from north to south with localized outflow into the major rivers. Groundwater gradient varies from 1:1000.

Groundwater is mainly abstracted by the installation of wells for the development of water supply systems. The major share of drinking water supplies are abstracted with suction hand-pumps but, as groundwater levels have a tendency to be deeper, a greater portion of water (around 20%) is abstracted with Tara pumps (a direct action hand pump which gives discharge both with the upward and downward stroke, capable of withdrawing water up to 15 m deep below the ground level) (DPHE/BGS/MML 1999).

METHODOLOGY AND DEVELOPMENT OF INTERPRETATION TECHNIQUE

The methodology consists of the identification of tubewells in the study area on a household basis. The tubewells were tested for arsenic contamination and relevant information such as the location of tubewell, year of construction, ownership, depth of well and type of well was recorded. The locations of tubewells were identified using GPS (Global Positioning System) equipment and conducted by BGS. The samples for arsenic contamination were measured by field test kit and laboratory analyses using spectrophotometric techniques. The gathered information was put into a database and used to generate a digitized map using ArcView. ArcView was used to create a map indicating arsenic-contaminated area with

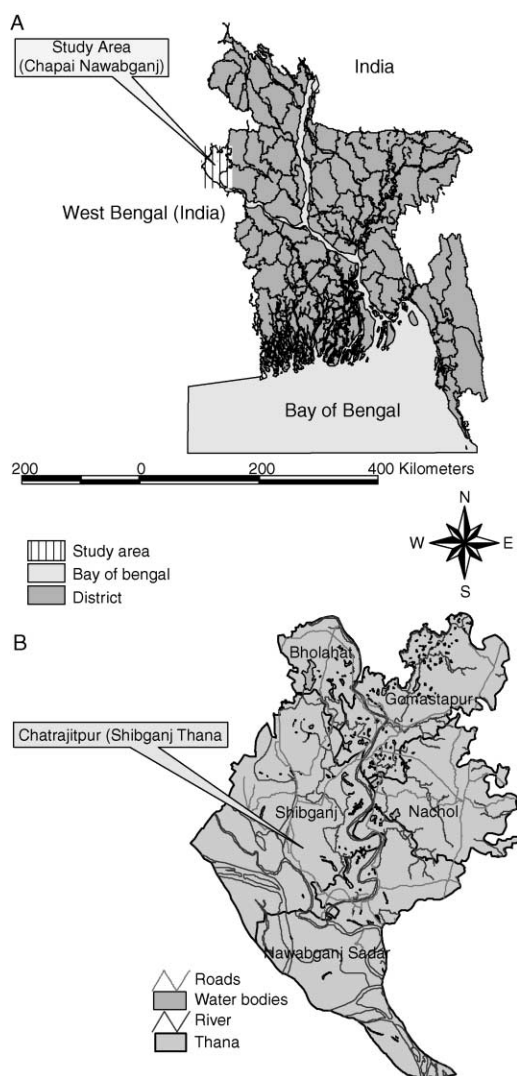


Figure 1 | (A) Map of Bangladesh showing the network of the rivers Ganges–Brahmaputra–Meghna and the location of the Chapai Nawabganj district. (B) Detailed map of the case study area of the Chapai Nawabganj district.

exposed population. Instant Traveling Expert Advice (InstantTEA), an expert system, was then used to recommend alternative options for safe drinking water in the study area. A survey was carried out to gather the users' responses on their arsenic problem. The mapping and interpretation technique is applied by policy makers and public health engineers at the district level who take mitigation measures that are feasible, adaptable and affordable by the people of the arsenic-contaminated area. The people in the affected areas are not capable of using such an interpretation technique as they lack even basic computing skills. Therefore, respondent feedback

to a system-generated survey questionnaire is recorded. This is carried out through NGO workers who then report the results to the Public Health Engineering office at the district level. The engineers then come up with a number of suitable alternative options, of which one is finally selected by the users of the arsenic affected areas.

Task analysis and formalization

The first important step is to collect data that will provide an understanding of the magnitude of the problem, then analyse those data to derive a solution based on different criteria. For mapping, a GIS is used for spatial analysis and InstantTEA is used for the selection of suitable options. When arsenic contamination is identified, the immediate priority must be to find a safe alternate source of drinking water for the affected communities. Alternative sources must not only be arsenic-free but also be microbiologically safe. There is a wide range of options available for arsenic-free safe water, which can be divided into two categories:

- (i) short-term options.
- (ii) long-term options.

The choice of option depends on affordability, feasibility and the urgency of the problem. If a safe water option is not available round the year, it may be necessary to use a specific source during the wet season (e.g. rainwater harvesting) and another during the dry season (e.g. arsenic removal filters). If a completely satisfactory, arsenic-free safe water source cannot be established, the short-term goal should be to reduce arsenic levels in drinking water as much and as quickly as possible. It should be recalled that the health effects of arsenic are dose-dependent and a partial solution is better than no solution. Table 1 presents an interpretation technique that is composed of three major tasks, which uses the algorithm developed on the basis of the users' responses presented in Figure 2.

Selection of building tools for the interpretation technique

It was suggested that the development process of an interpretation technique could be made considerably easier and more cost-effective through the use of tools that could

Table 1 | Major tasks performed during the formulation of the interpretation technique

Task types	Interpretation techniques
1. Spatial analysis	Risk analysis by creating a map with buffer distance Calculate area as well as number of population exposed to arsenic contamination
2. Selections of alternative options for safe drinking water	i) Hydrology Check for continuity of water supply Check for availability of surface water (Pond) ii) Cost analysis Check for the cost iii) User friendliness Check for ease of maintenance
3. Assessment of different options	Check for user responses on different options

be selected based on ease in manipulation and increased productivity. Without requiring any new or special knowledge representation techniques, most commercial expert systems can adequately cater for the needs of the chosen domain. The selected tools are ArcView and InstantTEA, which run on Microsoft Windows platforms.

Geographic Information System (GIS): ArcView

The database based on the case study has been developed using ArcView. GIS enables decision-makers to answer complex questions more quickly and more accurately compared to decision-makers when using paper maps. ArcView was used to display vector-based data to manipulate arsenic and related information in a customized applications environment. The arsenic-contaminated tube-wells were analyzed by surface interpolation provided from the Spatial Analysis extension of ArcView to generate a vulnerability map of the study area. The spline interpolator is used by the Spatial Analyst to interpolate sample points that fit a minimum-curvature surface through the input points. A mathematical function is fitted to a specified number of nearest input points, while passing through the sample points. This method is best for gently varying surfaces such as elevation, water table heights or pollution

concentrations. Thus ArcView produces its final product in the form of maps (showing the extent of arsenic contamination) or statistical reports (such as a table listing the number of people exposed to arsenic contamination).

Instant Traveling Expert Advice (InstantTEA)

InstantTEA, as shown in Figure 3, is an expert system that represents expertise in symbolic or numerical forms of modularized conditional rules that are easily modified and expanded (Ajward *et al.* 1999). The system is designed to improvise a technique based on a problem-solving approach within a narrow area of expertise based on reasoning rather than complex mathematical analysis (Beerel 1987). InstantTEA has been used for decision-making in identifying potential landfill sites as part of an expert system (Ajward *et al.* 2000). InstantTEA is an Integrated Development Environment (IDE) application and delivery applet for production and delivery of fuzzy knowledge bases on the Web (Figure 3).

The entire system is implemented in Java™ to allow delivery of expert advice over the Web anywhere and anytime. The delivery applet establishes a dialog with the user by applying knowledge bases created by the IDE. During the dialog session, a user points and clicks in

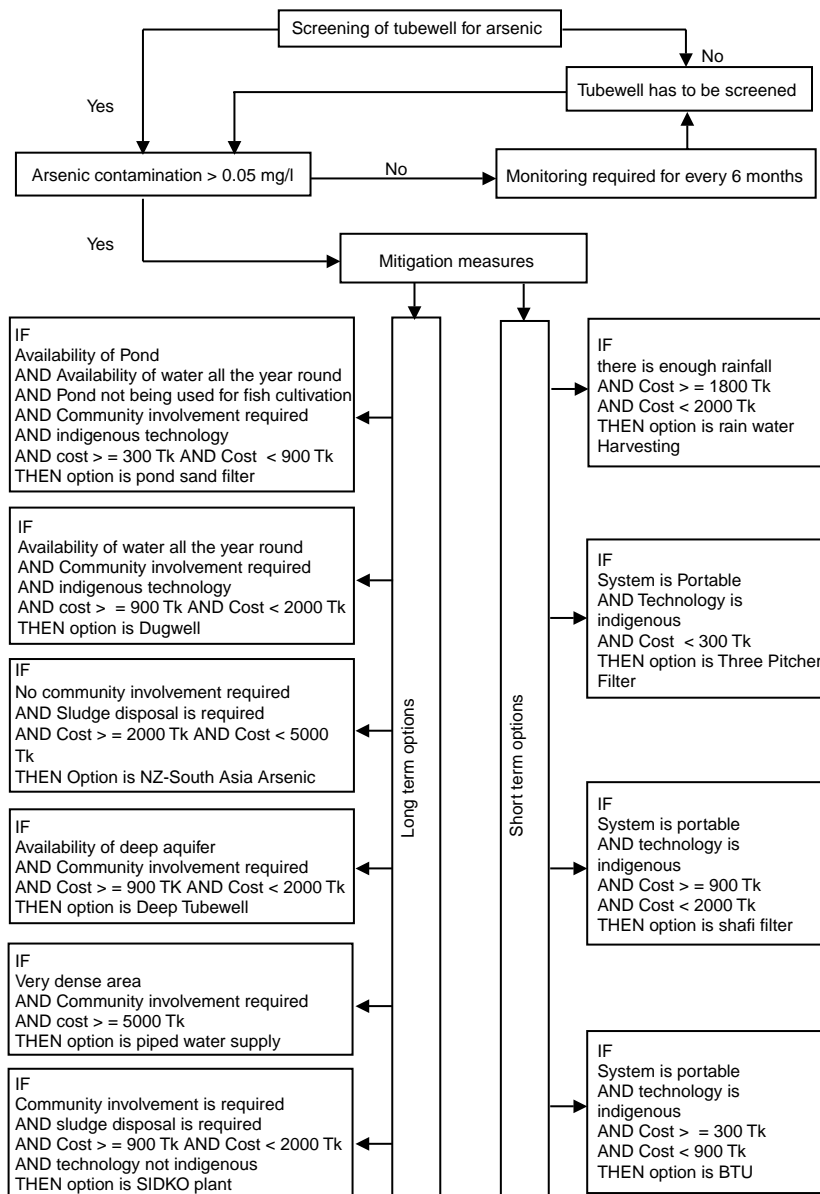


Figure 2 | Flowchart showing the algorithm for the interpretation technique. (Note: 1 BDT is equivalent to 0.01605 USD and 0.01215 Euro).

the browser to answer system-generated questions. Based on the extent of different queries such as type of options, hydrology, cost analysis and user friendliness, it will give recommendations for alternative safe water options as suitable mitigation measures. An advantage of using this module is that each browser window features an 'Explain' button. This feature explains the various technical terms and recommendations related to the queries.

InstantTEA uses only backward chaining of inference. Backward chaining is an algorithm that uses rules and deductive reasoning to logically draw conclusions. In this fashion, given that A is true and a rule 'IF A THEN B', then a valid inference is to conclude that B is true. The first part of the rule < IF > is called the premise and the second part < THEN > is called the conclusion. Backward chaining starts with picking the most likely

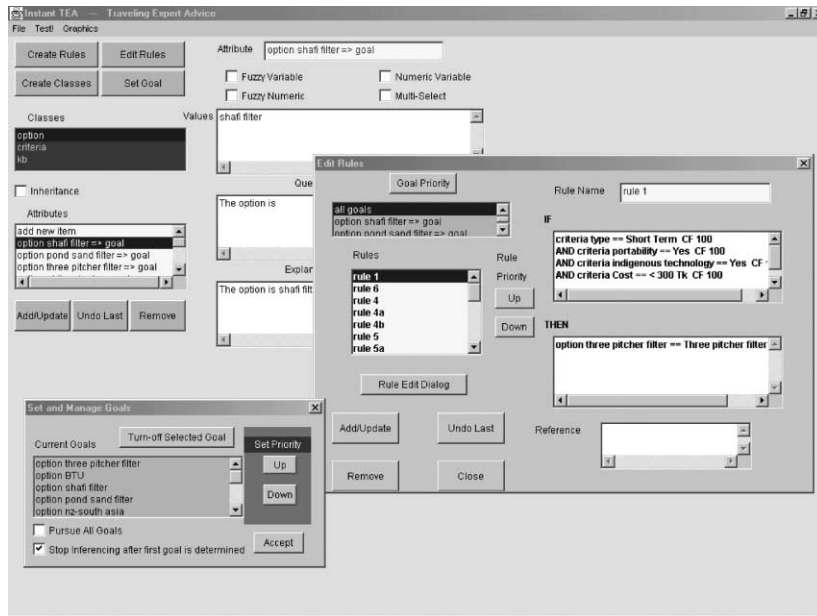


Figure 3 | Software layout for InstantTEA with different features.

hypothesis and working backward to prove that hypothesis. The following presents an example of backward chaining. Consider the following rules:

```

RULE
< IF >
Type of Option == Long Term
AND Availability of Pond == Yes
AND Availability of water all the year
round == Yes
AND Fish Cultivation in Pond == No
AND Cost == >= 300 TK
AND Cost == <= 900 TK
AND Community Involvement == Yes
< THEN >
Safe water option == Pond Sand Filter
ELSE
Choose == Other Options
  
```

The goal is to determine the safe water option as Pond Sand Filter. This goal is set in the construction of the knowledge base. The first step in backward chaining is to pick a rule to prove. Rule priority is important in deciding the initial hypothesis, so let us start with the rule and try to prove 'Safe water option == Pond Sand Filter'. The backward

chaining first looks at all the rules to see if any rule concludes 'Safe water option == Pond Sand Filter', as shown below:

```

System: What type of options do you prefer?
User: Long Term Option.
System: Is there any Pond available in the
locality?
User: Yes.
System: Is there water available all the year
round?
User: Yes.
System: Is the pond used for fish cultivation?
User: No.
System: How much are you willing to pay for safe
drinking water?
User: >= 5000 TK
System: Do you prefer community involvement?
User: Yes.
With those responses the system proves the
rule which concludes " Safe water option ==
Pond Sand Filter" and report its conclusion to
the user.
System: The safe water option is Pond Sand
Filter.
  
```

During the execution of InstantTEA, a dialogue window appears with system-generated questions to be responded to by the users as shown in Figure 4(a) and (b), respectively. This enables the system to recommend the type of option that is feasible in the area.

RESULTS AND DISCUSSIONS

The alternative options for safe drinking water mainly consist of the use of arsenic-free tubewells and dugwells. It was observed that, due to lack of availability of suitable options, 32% of households are still drinking arsenic-contaminated water from tubewells. Since the affordability of any suitable option is a key factor in the selection of alternative safe water options, people's willingness to pay for the possible options proved to be the most important criteria for the development of the knowledge base. Therefore, when people were asked how much they were willing to pay to obtain safe drinking water, the study showed that 42% of the total respondents are willing to pay less than 300 BDT (1 BDT = 0.016 05 USD, February 2005), 33% of them 300–899 BDT, 17% of them 900–1999 BDT and the remainder (8%) between 2000–4999 BDT respectively (Figure 5).

A number of alternative safe water options currently in practice in Chatrajitpur have been assessed based on user

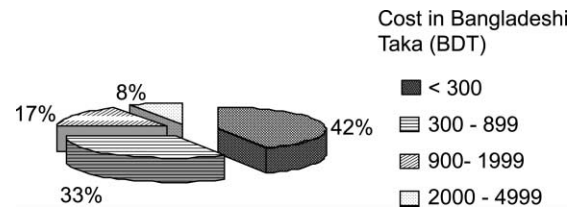


Figure 5 | Peoples willingness to pay for safe water options in the study area of Chatrajitpur, Shibganj Thana.

responses. Criteria such as cost, continuity of supply, ease of maintenance and social acceptability were used for evaluation of the different options. Table 2 presents a ranking of increasing suitability of the safe water options by using a scale of 1 through 5 (1 = Very Poor, 2 = Poor, 3 = OK, 4 = Good, 5 = Very Good). A rating over 3 represents the suitability of a specified option for drinking purposes. This assessment facilitates the selection of criteria as well as their relative importance in designing a knowledge base for system-generated questions.

The cost for assessment of different options based on users' responses includes both initial and running costs. However, criteria like technical effectiveness and susceptibility to bacteriological contamination were not considered as people in the study area lacked knowledge upon which those two criteria could be assessed. Based on the assessed score it was found that the three-pitcher

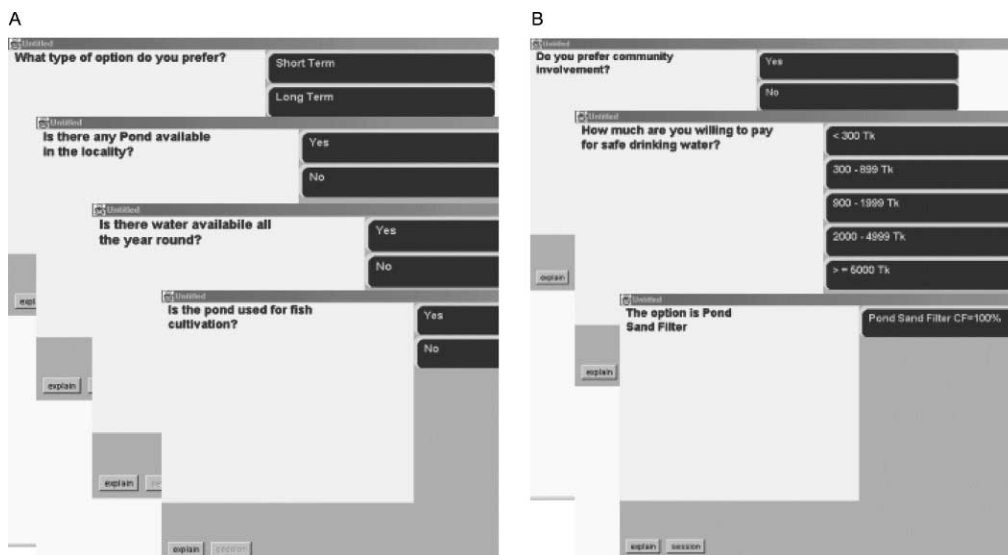


Figure 4 | (A) System-generated dialog box for the choice of options, pond, availability of water and fish cultivation. (B) System-generated dialog box for the response with community involvement, cost and recommendation of the options.

Table 2 | Assessment of different alternative safe water options based on users' responses

Criteria for evaluation	Pond sand filter	Dugwell	Rain water harvesting	Deep tubewell	Three pitcher filter	Shafi filter	Bucket treatment unit (BTU)	SIDKO plant	New Zealand-South Asia Bilateral Programme
Cost	1	3	4	1	5	4	5	1	1
Continuity of supply	4	3	1	5	4	3	3	3	3
Ease of maintenance	4	4	5	4	5	2	2	1	3
Social acceptability	4	4	4	4	5	3	3	3	3
Total score	13	14	14	14	19	12	13	8	10

filter is the most widely acceptable option based on cost, continuity of supply, ease of maintenance and social acceptability. Options like dugwells, pond sand filters and rainwater harvesting seem quite promising. This result is further incorporated in setting the priority of the development options for the knowledge base.

The vulnerability map generated by the analysis of ArcView reveals that an estimated population of 71 413 are located in a high risk zone, 140 298 are located in a medium risk zone and 199 957 are located in a low risk zone, as shown in Figure 6. This spatial analysis assists in identifying the areas where mitigation options are needed.

CONCLUSIONS

This mapping and interpretation technique facilitates the identification of potential areas exposed to arsenic contamination and assists decision-makers, particularly DPHE engineers, in selecting suitable options based on users' responses. The knowledge base in the system is designed to take into considerations the geological and hydrogeological characteristics, socio-economic conditions and socio-cultural behavior patterns of the people living in the area. Options like BTU (Bucket Technology Unit) and Shafi Filter, although used primarily for the removal of arsenic on a household scale as a short-term option, lacks continuous monitoring to be considered as a long-term

option for safe drinking water in affected areas. An advantage of the proposed interpretation technique is that a knowledge base can be easily built and any updated information or modification can be quickly incorporated into the knowledge base. Thus the knowledge base can be updated with new and low cost arsenic remediation options such as auto-attenuation, use of geological materials as natural adsorbents for arsenic, artificial recharge to the aquifers following aeration and bacterial iron oxidation (Bhattacharya *et al.* 2002). The knowledge base can also be updated with information on the availability of safe aquifers in a given arsenic-affected area based on critical hydro-geochemical investigations that can be targeted for the supply of safe drinking water (von Brömssen *et al.* 2005).

Since InstantTEA is platform-independent and internet-friendly, it can be accessed from anywhere via the internet through any browser. Any user with limited computer knowledge can easily use this application. All the modules of InstantTEA are simple, with just point-and-click options that follow one after another in sequence, eliminating confusion and complexity.

The interpretation would be more effective in forecasting the exact population exposed to arsenic contamination if each and every tubewell with its spatial distribution were entered into the database. By utilizing the efficiency of this system, less time and money needs to be spent in identification of severely contaminated areas. Rather, more resources can be allocated to alternative options

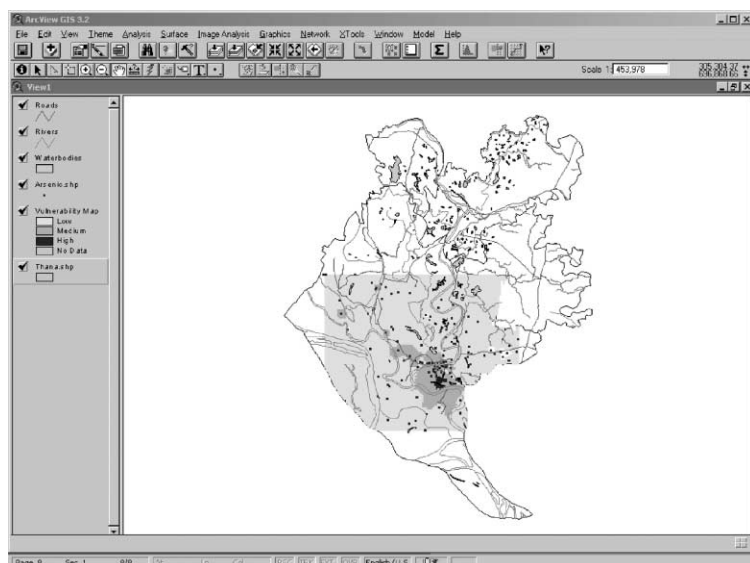


Figure 6 | Vulnerability map of Chapai Nawabganj district indicating the areas of groundwater arsenic contamination classified as high, medium and low risk zones.

that are feasible in the study area. Thus the developed mapping and interpretation technique can be a common platform for bringing together the stakeholders, policy makers, public health engineers and scientists working in the field of arsenic contamination.

Future research should focus on the integration of simultaneous mapping and interpretation. Web-based GIS tools such as ArcExplorer, ALOV Map and Jmapper could be used as a visualization tool while extending their capabilities by completely integrating with the interpretation technique. Though the mapping and interpretation technique is developed in the context of the geophysical, social and economical aspects of Bangladesh, there is a tremendous potential for application of this system in other countries of the world affected with arsenic contamination. Application of this technique in other locations would require that the knowledge base be modified and updated to reflect the specific characteristics of that particular country. Specifically, the application of a GIS coupled with an expert system is a potential tool for dissemination of quick information and knowledge not only for arsenic-affected areas of Bangladesh but also for other arsenic-affected countries of the world. In the future, an information system could be developed that would bring other arsenic regions in the world under the same platform of global information system where decision-makers, engineers and scientist have the opportunity to share

data, information and knowledge via the internet in the arsenic-related field.

REFERENCES

- Ahmed, K. M., Bhattacharya, P., Hasan, M. A., Akhter, S. H., Alam, S. M. M., Bhuyian, M. A., Imam, M. B., Khan, A. A. & Sracek, O. 2004 Arsenic enrichment in groundwater of the alluvial aquifers in Bangladesh: an overview. *Appl. Geochem.* **19** (2), 181–200.
- Ahmed, K. M. & Burges, W. G. 1995 Bils and the Barind aquifer, Bangladesh. In *Geomorphology and Groundwater*, (ed. A. G. Brown), Chapter 8 Wiley, New York, pp. 143–155.
- Ajward, M. H., Basri, H. & Fatimah 1999 Development of an expert geographic information system for siting of sanitary landfills for municipal solid waste, Kuala Lumpur, Malaysia. In *Proc. World Engineering Congress – Towards the Engineering Vision: Global Challenges and Issues. 19–22 July 1999, Kuala Lumpur, Malaysia*, Institution of Engineers, Malaysia, and Faculty of Engineering, Universiti Putra Malaysia. Malaysia pp. 154.
- Arnold, H. L., Odman, R. B. & James, W. D. 1990 *Andrews' diseases of the skin: clinical dermatology*, 8th ed., W. B. Saunders. Philadelphia, PA, pp. 121–122.
- Ajward, M. H., Basri, H. & Shams, S. 2000 Integrated expert system for municipal solid waste landfill siting in developing countries. *Proc. 16th International Conference on Solid Waste Technology and Management, 10–13 December 2000, Philadelphia, PA, USA*, Session 9C, School of Engineering, Widener University and the University of Pennsylvania. Chester, PA, USA. pp. 9-85–9-94.

- Beerel, A. C. 1987 *Expert Systems: Strategic Implications and Applications*. Ellis Horwood, Chichester.
- Bejarano, G. & Nordberg, E. 2003 Mobilisation of arsenic in the Río Dulce alluvial cone, Santiago del Estero Province, Argentina. Master Thesis. Department of Land and Water Resources Engineering, KTH Stockholm, Sweden, TRITA-LWR-EX-03-06.
- Berg, M., Tran, Y. H. C., Nguyen, T. C., Pham, H. V., Schertenleib, R. & Giger, W. 2001 Arsenic contamination of ground and drinking water in Vietnam: A human health threat. *Env. Sci. Technol.* **35**, 2621–2626.
- BGS & DPHE 2001 *Arsenic Contamination of Groundwater in Bangladesh. British Geological Survey Report WC/00/19* (eds. D. G. Kinniburgh & P. L. Smedley), vol. 2, Final Report.
- Bhattacharjee, S., Chakravarty, S., Maity, S., Dureja, V. & Gupta, K. K. 2005 Metal contents in the groundwater of Sahebgunj district, Jharkhand, India, with special reference to arsenic. *Chemosphere* **58**, 1203–1217.
- Bhattacharya, P., Claesson, M., Fagerberg, J., Bundschuh, J., Storniolo, A. R., Martin, R. A., Thir, J. M. & Sracek, O. 2005 Natural arsenic in the groundwater of the alluvial aquifers of Santiago del Estero Province, Argentina. In *Natural Arsenic in Groundwater: Occurrence, Remediation and Management* (eds. J. Bundschuh, P. Bhattacharya & D. Chandrashekharam), A A Balkema. London, pp. 57–66.
- Bhattacharya, P., Jacks, G., Frisbie, S. H., Smith, E., Naidu, R. & Sarkar, B. 2002 Arsenic in the environment: a global perspective. In *Handbook of Heavy Metals in the Environment* (ed. B. Sarkar), Marcel Dekker. New York, pp. 145–215.
- BRAC 2000 *Combating a Deadly Menace. Early Experiences with a Community-based Arsenic Mitigation Project in Bangladesh*. BRAC. Dhaka.
- Bundschuh, J., Farias, B., Martin, R., Storniolo, A., Bhattacharya, P., Cortes, J., Bonorino, G. & Albouy, R. 2004 Groundwater arsenic in the Chaco-Pampean Plain, Argentina: case study from Robles County, Santiago del Estero Province. *Appl. Geochem.* **19** (2), 231–243.
- Chakraborti, D., Sengupta, M. K., Rahman, M. M., Ahmed, S., Chowdhury, U. K., Hossain, M. A., Mukherjee, S. C., Pati, S., Saha, K. C., Dutta, R. N. & Quamruzzaman, Q. 2004 Groundwater arsenic contamination and its health effects in the Ganga-Megna-Brahmaputra plain. *J. Environ. Monit.* **6**, 74–83.
- Chowdhury, Q. I. 2000 Rural Bangladeshis at risk of arsenic poisoning. In *Bangladesh State of Arsenic* (ed. Q. I. Chowdhury), Forum of Environmental Journalists of Bangladesh (FEJB). Dhaka, pp. 11–14.
- Claesson, M. & Fagerberg, J. 2003 Arsenic in groundwater of Santiago del Estero – Sources, mobility patterns and remediation with natural materials. *TRITA-LWR-EX-03-05* Master Thesis. Department of Land and Water Resources Engineering, KTH Stockholm, Sweden.
- Criaud, A. & Foulliac, C. 1989 The distribution of arsenic (III) and arsenic (V) in geochemical waters: examples from the Massif Central of France, the Island of Dominica in the Leeward Islands of the Caribbean, the Valles Caldera of New Mexico, USA, and south-west Bulgaria. *Chem. Geol.* **76**, 259–269.
- Del Razo, L. M., Arellano, M. A. & Cebrian, M. E. 1990 The oxidation states of arsenic in well-water from a chronic arsenic area of northern Mexico. *Environ. Pollut.* **64**, 143–153.
- Dhar, R. K., Biswas, B. K., Samanta, G., Mandal, B. K., Chakraborti, D., Roy, S., Jafar, A., Islam, A., Ara, G., Kabir, S., Khan, A. W., Ahmed, S. A. & Hadi, S. A. 1997 Groundwater arsenic calamity in Bangladesh. *Current Sci.* **73**, 48–59.
- DPHE/BGS/MML 1999 *Groundwater Studies for Arsenic Contamination in Bangladesh. Phase I; Rapid Investigation Phase. vol 6*. British Geological Survey and Mott MacDonald. London.
- GOB 1997 *Environment Conservation Regulation*. Government of People's Republic of Bangladesh, Dhaka.
- Heywood, I., Cornelius, S. & Carver, S. 1998 *An Introduction to Geographical Information Systems*. Addison Wesley Longman, London.
- Hsu, K. H., Froines, J. R. & Chen, C. J. 1997 *Studies of arsenic ingestion from drinking water in northern Taiwan: chemical speciation and urinary metabolites* (eds. C. O. Abernathy, R. L. Calderon & W. R. Chappell), Chapman & Hall, London, pp. 190–209.
- Karim, Md. M. 2000 Arsenic in groundwater and health problem in Bangladesh. *Wat. Res.* **34** (1), 304–310.
- Marimuthu, P. 2001 Arsenic contamination in West Bengal and Bangladesh: statistical errors. *Environ. Health Perspective* **109** (2) Available at: <http://ehpnet1.niehs.nih.gov/docs/2001/109-2/correspondence.html>.
- Martin, D. 1996 *Geographic Information Systems: Socioeconomic applications*. Routledge, London.
- Mukherjee, AB & Bhattacharya, P. 2001 Arsenic in groundwater in the Bengal Delta Plain: slow poisoning in Bangladesh. *Environ. Rev.* **9** (3), 189–200.
- Nicolli, H. B., Suriano, J. M., Peral, M. A. G., Ferpozzi, L. H. & Baleani, O. A. 1989 Groundwater contamination with arsenic and other trace elements in an area of the Pampa, province of Corodoba, Argentina. *Environ. Geol.* **14** (1), 3–16.
- Niu, S., Cao, S. & Shen, E. 1997 The status of arsenic poisoning in China. In *Arsenic Exposure and Health Effects* (eds. C. O. Abernathy, R. L. Calderon & W. R. Chappell), Chapman & Hall, London, pp. 18–83.
- Samanta, G., Mandal, B. K., Chowdhury, T. R., Biswas, B. K., Chowdhury, U. K., Basu, G. K., Chanda, C. R., Lodh, D., Saha, K. C. & Chakraborti, D. 1999 Arsenic in groundwater and sufferings of people in eight districts of West Bengal, India. In *Proc 5th Int. Conf. on the Biogeochemistry of Trace Elements, 11–15 July 1999, Vienna, Austria vol I* (eds. W. W. Wenzel, D. C. Adriano, B. Alloway, H. E. Doner, C. Keller, N. W. Lepp, M. Mench, R. Naidu & G. M. Pierzynski), International Society of Trace Element Research, Vienna, Austria.
- Smedley, P. L., Noco, I. H. B., Barros, A. J. & Tullio, J. O. 1998 Origin and mobility of arsenic in groundwater from the Pampean Plain, Argentina. In *Proc. 9th International*

- Symposium on Water-Rock Interaction, Taupo, New Zealand, 30 March–3 April 1998* (eds. G. B. Arehart & J. R. Huston), Balkema, Rotterdam, WRI-9, pp. 275–278.
- Tandukar, N., Bhattacharya, P., Jacks, G. & Valero, A. A. 2005 Naturally occurring arsenic in groundwater of Terai region in Nepal and mitigation options. In *Natural Arsenic in Groundwater: Occurrence, Remediation and Management* (eds. J. Bundschuh, P. Bhattacharya & D. Chandrashekharam), A A Balkema, London, pp. 41–48.
- von Brömssen, M., Bhattacharya, P., Ahmed, K. M., Jakariya, M., Jonsson, L., Lundell, L. & Jacks, G. 2005 Targeting safe aquifers in regions with elevated arsenic in groundwater of Matlab Upazila, Bangladesh. In *Book of Abstracts, 8th Int. Conference on the Biogeochemistry of Trace Elements, Adelaide, Australia, April 3–7, 2005* (eds. E. Lombi, S. Tyrell, A. Nolan, M. McLaughlin, G. Pierzynski, M. Gerzabek, N. Lepp, C. Leyval, M. Selim, F. Zhao, C. Grant & D. Parker), Adelaide, Australia, pp. 190–191.
- Wang, L. & Huang, J. 1994 Chronic arsenism from drinking water in some areas of Xinjiang, China. In *Arsenic in Environment, Part II: Human Health and Ecosystem Effects* (ed. J. O. Nriagu), Wiley, New York, pp. 159–172.
- Welch, A. H., Lico, M. S. & Hughes, J. L. 1988 Arsenic in groundwater of the Western United States. *Ground Water* **26**, 333–347.
- WHO 2001 Arsenic contamination in drinking water in Bangladesh. *Fact Sheet No. 210*. WHO, Geneva. Available at: www.who.int/inf-fs/en/fact210.html
- Worboys, M. F. 1996 *GIS-A Computer Perspective*. Taylor & Francis, London.