Arsenic contamination of groundwater in Bangladesh

Vol 3: Hydrochemical atlas
Government of the People’s Republic of Bangladesh
Ministry of Local Government, Rural Development and Co-operatives
Department of Public Health Engineering

Department for International Development (UK)

British Geological Survey

BGS Technical Report WC/00/19, Volume 3

Arsenic contamination of groundwater in Bangladesh

Vol 3: Hydrochemical atlas

D G Kinniburgh and P L Smedley (Editors)

February 2001
The full report comprises four volumes:
Volume 1. Summary
Volume 2. Final report
Volume 3. Hydrochemical atlas
Volume 4. Data compilation

Further information can also be viewed and downloaded from our website at www.bgs.ac.uk/arsenic/Bangladesh

This document is an output from a project funded by the UK Department for International Development (DFID). The views expressed are not necessarily those of DFID.

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Cover Illustration
Map of Bangladesh showing the regional distribution of arsenic in groundwater found during the National Hydrochemical Survey

Bibliographic Reference
BGS AND DPHE, 2001
Arsenic contamination of groundwater in Bangladesh
KINNIBURGH, D G and SMEDLEY, P L (Editors)
Volume 3: Hydrochemical atlas
British Geological Survey Report WC/00/19
British Geological Survey, Keyworth.

ISBN 0 85272 384 9

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1 The National Hydrochemical Survey

The DPHE/BGS National Hydrochemical Survey (NHS) was carried out in two phases during March-June 1998 and May-July 1999, principally to investigate the distribution of arsenic in Bangladesh groundwaters. However, advantage was taken of the effort involved in sample collection to also assess the distributions of other related or otherwise diagnostic constituents of Bangladesh groundwaters. The survey involved the collection of 3534 groundwater samples from tubewells in 61 out of the 64 districts of Bangladesh and 433 of the 496 upazillas. The three districts excluded belonged to the Chittagong Hill Tracts. This resulted in a sample density of around 8 samples per upazila on average, or approximately one sample per 37 km².

The sampled wells are only a very small proportion, approximately 0.05–0.1%, of the total number of wells. Nonetheless, every effort was made to sample the wells as randomly as possible given various practical constraints. Specifically sample selection was made without prior knowledge of arsenic concentrations. Most wells sampled were Government-drilled (DPHE) wells since it was relatively easy to determine details of their age, depth and construction. They were thought to be similar in construction to the more abundant private wells. This was a critical consideration in choosing the sampling strategy adopted by the survey. Discussion of the sampling strategy, sample collection and analysis is given in more detail in the National Hydrochemical Survey chapter of the Main Report.

Maps of the various parameters measured are given in the following pages. When plotting the maps, class boundaries for most parameters were based on rounded quartile values, i.e. each class interval contained approximately the same number of wells. This enabled any overall pattern to be clearly seen irrespective of the absolute range of values. The actual percentage of wells in each class interval is given by the histograms seen in the insets to the NHS maps. However, some of the health-related elements (arsenic, manganese, barium, boron, fluoride, iodide) are also divided according to WHO guideline values, Bangladesh standard values or otherwise useful class boundaries.

The class intervals used in the BWDB maps were the same as for the NHS maps. The Mandari village maps were based on rounded quartile values for this area rather than the NHS values. In the case of well depth, class boundaries are on the basis of rounded quartiles, except that the deepest quartile has been further subdivided into ≤50 m and >150 m categories. Each parameter includes a map, statistical summary, histograms, a variogram and discussion. Discussion of the distributions in many cases uses the physiographic classification of Bangladesh given by Alam et al. (1990).

The atlas also includes maps of groundwater chemistry from the survey of the 113 sites sampled from the BWDB Water-Quality Monitoring Network as well as from more detailed investigations in the project’s three Special Study Areas. These surveys include a more comprehensive set of chemical constituents than was possible in the National Survey.

The appearance of maps depends strongly not only on the underlying data but also on various subjective decisions made in preparing the maps: the extent of data smoothing, if any; the colours chosen and the way that these are interpreted by the display device (printer or monitor); the number of class intervals used; the symbols used, if any; their size and the order in which the symbols are printed. The order of printing may affect the appearance of the map where there is overlap of the symbols. In most of the point source maps given here, the number of classes was limited to four since it is often only possible to display at most four distinctive colours without fear of confusion. The lowest concentration class symbols were plotted first, then the next higher class, and so on, finishing with the highest concentration class. This means that, if anything, the maps will tend to overemphasise the importance of the higher classes since these class symbols will be plotted on top of any overlapping lower class symbols. In general, this effect is not large but care has to be taken when interpreting clusters of points in the NHS maps.

All of the 3534 samples from the NHS were analysed for arsenic and all but four were also analysed for a wide range of other major and minor elements. Most of these elements were determined by ICP-AES in the BGS laboratories. Arsenic was determined by either ICP-AES with hydride generation or more usually by AFS with hydride generation. Results from both methods were in good agreement. Filtered (0.22 µm) samples were always used. A range of trace elements, which is shown in the Special Study Areas and BWDB maps, was determined by ICP-MS. Chloride, nitrate, alkalinity, nitrite, ammonium, fluoride, bromide and iodide are also given in the Special Study Areas maps, and chloride, fluoride and iodide in the BWDB Water-Quality Monitoring Network maps. These were measured by automated colorimetry in the BGS laboratories (some bromide analyses were carried out by ion chromatography). Further details of sampling and analytical methods are given in Chapter 7 of the Main Report. Only elements substantially above detection limits have been included.

Gif and pdf images of the maps, as well as the underlying data files, can be downloaded from the BGS website at www.bgs.ac.uk/arsenic/Bangladesh. A fuller discussion of the maps and their significance is given in the appropriate chapters of the main report.
SAMPLES

The survey was carried out in two phases: the first phase (March–June 1998) covered what were at the time believed to be the worst-affected southern and eastern districts of Bangladesh while the second phase (May–July 1999) completed the remainder of Bangladesh apart from the three districts of the Chittagong Hill Tracts (CHT). Sample locations for the National Hydrochemical Survey are given in Sample location map. At the printed scale, the text in this map is too small to read but the field sample numbers (e.g. RIP1234) can be read by zooming in on the pdf file.

The CHTs were excluded from this national survey because at the time of initiating this survey, the predominantly older sediments of the CHTs were not thought to give rise to high arsenic groundwaters. This is still believed to be the case. Groundwater is used less in the CHTs and existing wells are relatively sparse and often remote and difficult to access. Including the CHTs during the Rapid Investigation Phase would have detracted from what were known to be areas of higher priority elsewhere. We were also aware that our chosen sample density for the main survey was in any case low in relation to the likely scales of variation.

The basic sampling strategy was based on a stratified random approach in which the stratification was by area. The aim was to sample the survey area as uniformly spatially as feasible, and within each strata (approximately 1/9 of a upazila) to select a well randomly. In the event some areas were more sparsely sampled than others, mainly due to poor site accessibility (lack of roads, flooded areas). Site accessibility was a particular problem in the Sundarbans area of the south west and in the flooded haor regions of the Sylhet and Atrai Basins. Lack of available wells was also a factor in the Madhupur Tract.
Year sampled

- 1998
- 1999

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DPHE/BGS/DFID (2000)
For each groundwater sample collected, the equivalent surface geological unit is given in the accompanying map. Data and standard abbreviations are taken from the 1:1,000,000 geological map of Bangladesh (Alam et al., 1990) and from digitised maps prepared by EGIS. It is important to note that the map indicates the geology at the surface and not at the depth of the aquifer from which the groundwaters were abstracted. With increasing well depth these are likely to be less related. However, many of the chemical features of the Bangladesh groundwaters do show some spatial correlation with the surface geology and so this is retained as a potentially useful attribute. The classification was carried out automatically using the recorded GPS reading and the digitised geological database. There may therefore be some misclassification close to geological boundaries or where the resolution of the map was insufficient to capture the true field variation.

A simplified geological map of Bangladesh is shown below. The geology is dominated by the delta environment which defines the borders of Bangladesh. The major features are the recent (Holocene age) deltaic sediments in southern Bangladesh, the alluvial sediments of central Bangladesh, the alluvial sediments of central Bangladesh (also Holocene) and older Pleistocene sediments of the uplifted Barind and Madhupur Tracts.

For each groundwater sample collected, the equivalent surface geological unit at that site was allocated by GIS using a digitized form of the geological map. The distribution of geological units sites is given in the map. Data and standard abbreviations (Table 1.1) are taken from the 1:1,000,000 geological map of Bangladesh (Alam et al., 1990) and from digitised maps by EGIS. It is important to note that the map indicates the geology at surface and not at the depth of the aquifer from which the groundwaters were abstracted. With increasing well depth these are likely to be less related. However, many of the chemical features of the Bangladesh groundwaters do show some spatial relationship with the surface geology.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>asl</td>
<td>Alluvial silt and loam</td>
</tr>
<tr>
<td>asc</td>
<td>Alluvial silt and clay</td>
</tr>
<tr>
<td>dsl</td>
<td>Deltaic silt and loam</td>
</tr>
<tr>
<td>dt</td>
<td>Tidal deltaic deposits</td>
</tr>
<tr>
<td>ppc</td>
<td>Marsh clay and peat</td>
</tr>
<tr>
<td>afy</td>
<td>Young gravelly sand</td>
</tr>
<tr>
<td>ac</td>
<td>Chandina alluvium</td>
</tr>
<tr>
<td>asd</td>
<td>Alluvial sand</td>
</tr>
<tr>
<td>afo</td>
<td>Old gravelly sand</td>
</tr>
<tr>
<td>ava</td>
<td>Valley alluvium &amp; colluvium</td>
</tr>
<tr>
<td>rm</td>
<td>Madhupur clay residuum</td>
</tr>
<tr>
<td>rb</td>
<td>Barind clay residuum</td>
</tr>
<tr>
<td>dc</td>
<td>Estuarine deposits</td>
</tr>
<tr>
<td>dsl</td>
<td>Deltaic sand</td>
</tr>
<tr>
<td>QTdd/QTdt/Tt</td>
<td>Dihing &amp; Dupi Tila undiv./Dupi Formation</td>
</tr>
<tr>
<td>QTdd/QTdt/Tt</td>
<td>Tila Formation/Tipam Sandstone Formation</td>
</tr>
</tbody>
</table>
Bangladesh - simplified geology

After Alam et al. (1990)
'Groundwater Studies of Arsenic Contamination in Bangladesh'
DPHE/BGS/DFID (2000)
**AGE OF WELL**

The oldest well sampled was constructed in 1937 and the most recent in 1999, the year of the second phase of the sampling. Construction of tubewells did not start in earnest until the 1970s and then expanded at an exponential rate.

The histogram opposite illustrates the considerable growth in the number of installed tubewells in recent years. 41% of the sampled wells have been installed since 1995 and 68% (two thirds) since 1990. About half of the wells have been constructed in 1993 or more recently and two thirds since 1990. This points to the significant expansion in the installation of tubewells by DPHE in recent years. Most of the tubewells sampled during the National survey were DPHE-constructed wells but there has also been a parallel increase in the number of private tubewells. The total number of wells in Bangladesh is not known with certainty but is believed to be somewhere in the region of 6–11 million, mostly private wells. DPHE are believed to have installed approximately 1.3 million wells.

There are regional variations in the age distribution with the greatest percentage of ‘old’ (pre-1980) wells sampled in the Khulna area and the smallest percentage in the Rajshahi area and north-western Bangladesh.
Year of construction
- before 1970
- 1975–1979
- 1980–1984
- 1985–1989
- 1990–1994
- 1995–1996
- since 1997

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DPHE/BGS/DFID (2000)
**WELL DEPTH**

Sampled wells in the National Hydrochemical Survey had a very large range of depths – these ranged from 7 m to 362 m. Sampled well depths also show a large spatial variability, but some distinct geographical patterns exist (Table 1.4). The shallowest groundwaters (<22 m) are mainly concentrated in the Tista Fan area of northern Bangladesh, the Jamuna (Brahmaputra) valley, the eastern part of the Barind Tract and in coastal areas of the south-east and south-west. In the coastal areas, groundwater is either abstracted from very shallow levels or very deep levels (>150 m) as a result of high salinity at intermediate depths. Deep groundwaters are also found in the north-eastern parts of Bangladesh as a result of lack of availability of good aquifers (sands) at shallower levels.

As drilling and well completion is usually restricted to the shallowest levels at which water is struck, the well depth map indicates the minimum depth at which acceptable quantities (or in the case of salinity, quality) of groundwater can be found.
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**ARSENIC**

The point-source maps for arsenic show the distributions based on both rounded quartiles and on health criteria, including the WHO guideline value of 10 µg L\(^{-1}\) and the Bangladesh standard for arsenic of 50 µg L\(^{-1}\). The maps include groundwaters from both the shallow (≤50 m depth) and deep (>150 m) aquifers. The rounded quartile map is also displayed in terms of a gray scale. A high resolution and detailed map of the arsenic point source data is also given. This map can be downloaded from the BGS website and is best printed at A2 portrait size (42.0 cm x 59.4 cm) using a colour printer.

The maps indicate the large spatial variability in arsenic concentrations. Concentrations range between <0.25 µg L\(^{-1}\) and 1660 µg L\(^{-1}\) with an overall median value in the shallow groundwaters of 6 µg L\(^{-1}\) and in the deep groundwaters of about 1 µg L\(^{-1}\). Considering the shallow groundwaters only, 47% exceed the WHO guideline value and 27% exceed the Bangladesh standard. Only 3 out of the 327 deep wells sampled (1%) exceed 50 µg L\(^{-1}\).

Despite the variability, some distinct regional patterns exist. These patterns are best revealed by smoothing the point source data. We did this using a technique called disjunctive kriging after transforming the data with Hermite polynomials (for details, see the Scales of variation chapter in the main report). Other smoothing techniques would give broadly similar patterns. The maps show distinct regional trends with a clear geological control. Low arsenic concentrations tend to be found in the older sediments.

However, given the very high degree of village-scale spatial variability observed, care has to be taken when interpreting this smoothed map. There will be wells within ‘low’ arsenic (blue) areas that are high in arsenic and wells within ‘high’ arsenic (red) areas that are low in arsenic. The map shows average concentrations that reflect regional patterns but it does not give any indication of the variability of individual wells around these average values. Normally, one of the advantages of kriging is that it is possible to produce a map of the associated variances (or errors) associated with a kriged map. However, because of the high censoring of the data at low concentrations, we were not confident enough of these variances to present them here.

The greatest proportion of high-arsenic wells (and the highest average arsenic concentrations) are in the southeast of Bangladesh, to the south of Dhaka. High concentrations are also found in the groundwaters of the Jamuna Valley and with patchy high values in the south-west and the north-east (Sylhet Basin). Sporadic highs (’hot spots’) are also found in other areas. One such hot spot is that of Chapai Nawabganj in the extreme west and is described more fully in the Main Report, Chapter Special Study Areas.

Despite the considerable variability, the patterns of arsenic distribution often show a good relationship with surface geology. Low concentrations are picked out well in the older Pleistocene plateaux of the Barind and Madhupur Tracts. This reflects the older age of the Dupi Tila aquifer from which these groundwaters are abstracted, having a longer history of groundwater flow and flushing. Low concentrations are also found in the deep groundwaters from the southern coastal area (Barisal). During past Quaternary glacial intervals, relative sea levels would have been much lower than at present (around 120 m at ca. 21 ka BP). This would have involved greater groundwater hydraulic gradients, lower river base levels and hence much active groundwater flow and flushing, as well as longer history of sediment diagenesis. Sediment age, groundwater flow history and amounts of flushing are considered to be major factors in determining the arsenic concentrations in the Bangladesh aquifers.

The highest arsenic concentrations and the greatest proportion of high-arsenic wells are in the Holocene alluvial and deltaic sediments. The overall worst-affected area in the south-east generally correlates with the low-lying (distal) part of the Bengal delta, where sediments are on average more fine-grained than further upstream and groundwater flow rates are likely to be slowest. The groundwaters in the worst-affected area are strongly reducing and show evidence of sulphate reduction. Some contain methane.

High arsenic concentrations are also found in some groundwaters from the Holocene sediments of the Jamuna Valley. These are also reducing groundwaters, although they appear to be more oxidising than the high-arsenic groundwaters further south. Groundwaters from this area have some of the highest concentrations of iron in Bangladesh (up to 48 mg L\(^{-1}\) and often >10 mg L\(^{-1}\)) and manganese (up to 10 mg L\(^{-1}\)) and higher overall sulphate concentrations (see maps) than the high-arsenic groundwaters further south. It is thought that these sediments are undergoing reduction but have reached less advanced stages than those further south. This may be for a number of reasons, including less abundant impermeable material (silt/clay) at surface, shallow tubewells and deeper water levels (greater thickness of unsaturated zone) and perhaps more active groundwater flow.

However, the high-arsenic groundwaters in the Jamuna Valley have mostly very low sulphate concentrations (typically 1 mg L\(^{-1}\) or less) and are hence more strongly reducing. It is possible that the high-sulphate wells from the Jamuna Valley result from some sulphide oxidation, although if this is happening, it is not associated with arsenic mobilisation. The general association of high arsenic concentrations with low sulphate in the Jamuna Valley, as elsewhere in Bangladesh, precludes the process of sulphide oxidation as the major cause of arsenic release.

Low overall concentrations of arsenic are found in northern Bangladesh in the Tista Fan sediments. These are more coarse grained than the sediments in the distal parts of the delta, lack an overlying impermeable layer, groundwaters are shallow and groundwater gradients greater. This part of the aquifer is therefore relatively oxidising and more actively flushed.

The smoothed arsenic map highlights the low arsenic concentrations of the uplifted Pleistocene plateaux in north central Bangladesh (Barind and Madhupur Tracts) and the Tista Fan in the extreme north. It also emphasises the worst-affected area of Bangladesh in the south-east.
Arsenic ($\mu$g L$^{-1}$)

- <0.5
- 0.5–4
- 4–50
- >50

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Arsenic contamination of groundwater in Bangladesh

Arsenic (health) (µg L⁻¹)
- <5
- 5–10
- 10–50
- 50–200
- >200

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DPHE/BGS/DFID (2000)

Bay of Bengal
India

27° 26° 25° 24° 23° 22° 21°
88° 89° 90° 91° 92° 93°

Percentage distribution

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DPHE/BGS/DFID (2000)
'Groundwater Studies of Arsenic Contamination in Bangladesh'  
DPHE/BGS/DFID (2000)
Arsenic contamination of groundwater in Bangladesh
Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/DFID (2000)
The estimated population exposed to arsenic in the drinking water from the smoothed distribution (kriging to a 5 km grid) is about 35 million at greater than 50 µg L⁻¹ and 57 million at greater than 10 µg L⁻¹. This differs slightly from estimates based on upazila-averaged statistics, which are around 28 million and 46 million people respectively. The problem is clearly very large.

Maps plotted with different concentration thresholds of arsenic are also shown for the shallow (≤150 m) wells. In these maps, the colour of a plotted tubewell is determined by whether it is below (blue) or above (red) the given threshold value, namely 5, 10, 25, 50, 100 and 200 µg L⁻¹. The maps become progressively more blue as the threshold value is raised. This is a useful way of highlighting the few very high arsenic wells.

These threshold maps show clearly the area of relatively low arsenic concentrations in the shallow wells that are found following the present-day Gorai River Valley in the Kushtia region and which extends southwards through Khulna and the Pusur and Sibsa Valleys near Bhairab to the Bay of Bengal. This Gorai-Bhairab feature could reflect the course of an old main river channel, possibly the palaeo-Attrai (see the ‘Geology and Sedimentology’ Chapter in the Final Report).
Barium

Concentrations of barium have a similar range in both the shallow and deep groundwaters of Bangladesh. (<0.06 mg L\(^{-1}\) to 1.4 mg L\(^{-1}\) and <0.06 mg L\(^{-1}\) to 1.0 mg L\(^{-1}\) respectively). Despite much spatial variability, the map shows some regional trends in barium concentration in the groundwaters. Highest concentrations are found most prevalently in the south-west of Bangladesh. More patchy highs are found in the Jamuna Valley and the north-east (Sylhet Basin). The highest concentrations to some extent reflect those of the other alkaline earth elements (calcium, magnesium, strontium) but the spatial distribution is much less distinct. Barium concentrations are likely to be limited dominantly by the solubility of barite. This may to some extent explain why barium concentrations are generally lower in northern Bangladesh, as sulphate concentrations are correspondingly relatively high.
Barium (mg L$^{-1}$)
- <0.03
- 0.03–0.06
- 0.06–0.12
- >0.12

Groundwater Studies of Arsenic Contamination in Bangladesh
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CONCENTRATIONS OF BORON VARY BETWEEN <0.01 mg L$^{-1}$ AND 1.6 mg L$^{-1}$ IN THE SHALLOW GROUNDWATERS AND BETWEEN <0.01 mg L$^{-1}$ AND 2.2 mg L$^{-1}$ IN THE DEEP GROUNDWATERS. THE DISTRIBUTION OF HIGH BORON CONCENTRATIONS ALSO SHOWS MANY SIMILARITIES WITH SODIUM. SODIUM CONCENTRATIONS ARE RELATIVELY HIGH IN THE DEEP GROUNDWATERS (MAINLY SAMPLED FROM NEAR-COASTAL BARI AND FROM SYLHET), WITH A MEDIAN VALUE OF 238 mg L$^{-1}$ COMPARED TO 38 mg L$^{-1}$ IN THE SHALLOW GROUNDWATERS. HIGHEST BORON CONCENTRATIONS ARE FOUND IN THE SOUTH AND SOUTH-EAST OF THE COUNTRY AND IN THE HAOR REGION OF NORTH-EASTERN BANGLADESH. RELATIVELY HIGH CONCENTRATIONS ARE ALSO FOUND IN THE GROUNDWATERS FROM THE ATRAI FLOODPLAIN IN THE WEST. THE REGIONAL HIGHS ARE BELIEVED TO REFLECT THE DISTRIBUTION OF SALINE GROUNDWATER RESULTING FROM PAST MARINE INUNDATION. HIGHEST CONCENTRATIONS ARE FOUND IN THE SOUTH AND SOUTH-EAST OF THE COUNTRY AND IN THE HAOR REGION OF NORTH-EASTERN BANGLADESH. RELATIVELY HIGH CONCENTRATIONS ARE ALSO FOUND IN THE GROUNDWATERS FROM THE ATRAI FLOODPLAIN IN THE WEST WHICH IS ALSO THOUGHT TO REFLECT A PALAEOSALINITY SIGNATURE.

THE 1998 WHO GUIDELINE VALUE FOR BORON IN DRINKING WATER IS 0.5 mg L$^{-1}$. ONLY 5% OF GROUNDWATERS FROM THE NATIONAL HYDROCHEMICAL SURVEY (ALL SAMPLED GROUNDWATERS) EXCEEDED THIS VALUE, MOST BEING FROM THE SOUTHERN COASTAL REGION AND FROM THE NORTH-EASTERN HAOR REGION. CONSIDERING THE DEEP AQUIFER ALONE, 30% OF SAMPLES EXCEEDED 0.5 mg L$^{-1}$. IN THESE HIGH-BORON GROUNDWATERS, THE SODIUM CONCENTRATION USUALLY EXCEEDED 200 mg L$^{-1}$. THE SEAWATER BORON CONTRIBUTION FOR A GROUNDWATER WITH 200 mg L$^{-1}$ Na (ALL ASSUMED TO BE DERIVED FROM SEAWATER) WOULD BE ONLY 0.082 mg L$^{-1}$ AND SO IT IS LIKELY THAT SOME SODIUM HAS BEEN PREFERENTIALLY FLUSHED FROM THE AQUIFER AS IT HAS FRESHENED.
**CALCIUM**

Groundwaters from most of the Bangladesh aquifers appear to be of calcium-bicarbonate type, with the exception of more saline groundwaters, predominantly near the coast, which have sodium as the dominant cation. In most Bangladesh groundwaters therefore, calcium is an important component. Concentrations range between 0.01 mg L⁻¹ and 366 mg L⁻¹ in the shallow groundwaters and between 0.4 mg L⁻¹ and 280 mg L⁻¹ in the deep groundwaters. Median concentrations are 35 mg L⁻¹ in the shallow aquifers and 17 mg L⁻¹ in the deep aquifers, the differences reflecting higher salinity of the sampled deep groundwaters.

There is a notable spatial variation in calcium concentrations that relates to sediment type and provenance and to soil type. Soils from south-western Bangladesh are calcareous. The aquifers from this region, composed of sediments associated with the Ganges (Padma) river system and derived from source regions in the west, also probably contain free carbonate minerals. Dissolution of carbonate in the sediments, principally calcite but also possibly dolomite, is likely to have given rise to the relatively high concentrations. The divide between high-calcium and low-calcium groundwaters is a sharp line on the north side of the Atrai Floodplain.

Especially low calcium concentrations are found in groundwaters from the Tista Fan deposits and the Sylhet Basin, both of which have non-calcareous grey and dark grey soils and in parts of the north-east (Sylhet), some deposits of peat. Low concentrations are also found in the deep groundwaters from the south coastal area (Barisal–Patuakhali).
The National Hydrochemical Survey

Calcium (mg L$^{-1}$)
- $<$15
- 15–30
- 30–80
- $>$80

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Groundwater hardness has been calculated by the summation of analysed calcium and magnesium concentrations and is expressed as meq L\(^{-1}\). The smoothed map shows the distribution of hardness in the Bangladesh groundwaters.

As expected, the regional distribution shows the same trends as for calcium and magnesium, i.e. the hardness is greatest in the southern half of Bangladesh where the sediments tend to contain carbonate minerals and where the residual marine influence is also greatest. Most Bangladesh groundwaters would be classified as ‘hard’. The maximum hardness is 35 meq L\(^{-1}\) (1 meq L\(^{-1}\) is equivalent to 50 mg CaCO\(_3\) L\(^{-1}\)) and is found in a shallow (13 m depth), saline groundwater from Pirojpur district in the southern coastal region. The median hardness in the shallow groundwaters is 3.3 meq L\(^{-1}\) whereas the median for the deep groundwaters is 1.8 meq L\(^{-1}\). The hardest waters, which quite often have a hardness exceeding 12 meq L\(^{-1}\), are widely scattered across southern Bangladesh while the softest waters with a hardness of less than 0.25 meq L\(^{-1}\) are concentrated in the Sylhet region. The deep groundwaters from the Patuakhali region are relatively soft.
Hardness (meq L⁻¹)

- <1.5
- 1.5–3
- 3–6
- >6

"Groundwater Studies of Arsenic Contamination in Bangladesh" 
DPHE/BGS/DFID (2000)
Iron

Iron concentrations in the groundwater range between <0.004 and 61 mg L$^{-1}$, with median values of 1.4 mg L$^{-1}$ and 0.2 mg L$^{-1}$ in the shallow and deep groundwaters respectively. Concentrations are high in most of the groundwaters of Bangladesh as a result of the predominance of reducing conditions in the aquifers. Concentrations are high but patchy in the south (south of the River Ganges) and in the north-east. The proportion of wells with high iron concentrations and the concentrations themselves are particularly high in the Jamuna Valley, with many exceeding 10 mg L$^{-1}$.

Lowest overall concentrations are found in the groundwaters from the Barind and Madhupur Tracts, the deep groundwaters of Barisal and in north-western parts of the Tista Fan. These patterns are clearly shown in the smoothed iron map (Figure 1.3). The Dupi Tila aquifers of the Barind and Madhupur Tracts and the deep aquifers of Barisal are older (Plio-Pleistocene) sediments with longer histories of groundwater flow and sediment diagenesis. The sediments of the Barind and the Madhupur Tracts are commonly brown or yellowish brown in colour and reflect past episodes of oxidation. The iron in these groundwaters may therefore be less labile than that associated with the younger Holocene deposits. In the Tista Fan, the low concentrations probably relate to the occurrence of relatively oxidising conditions (with presence of oxidised sands in the aquifers), coarse sediment grain size and relatively active groundwater movement.
Iron (mg L$^{-1}$)
- <0.15
- 0.15–1.0
- 1–5
- >5

Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/DFID (2000)
Iron (mg L⁻¹)

- <0.18
- 0.8–1.4
- 1.4–2.1
- 2.1–2.8
- 2.8–3.5
- 3.5–4.1
- 4.1–5
- 5–7
- 7–10
- >10

'Groundwater Studies of Arsenic Contamination in Bangladesh'
DPHE/BGS/DFID (2000)
**Magnesium**

Magnesium concentrations range between <0.04 mg L\(^{-1}\) and 305 mg L\(^{-1}\) in the shallow groundwaters and between 0.7 mg L\(^{-1}\) and 137 mg L\(^{-1}\) in the deep groundwaters, with median values of 16 mg L\(^{-1}\) and 11 mg L\(^{-1}\), respectively. The distribution of magnesium in the groundwaters closely resembles that of calcium (Figure 1.x) and is likely to result from the dissolution of free carbonate minerals in the aquifers and overlying soils. Some of the magnesium in groundwaters from southern Bangladesh is also likely to be related to saline intrusion as seawater has relatively high magnesium concentrations (around 1300 mg L\(^{-1}\)).
Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/DFID (2000)
MANGANESE

Concentrations of manganese in the Bangladesh groundwaters were measured between <0.002 mg L$^{-1}$ and 10 mg L$^{-1}$. Median concentrations in the shallow and deep aquifers respectively were 0.34 mg L$^{-1}$ and 0.03 mg L$^{-1}$. This highlights the large difference in concentrations between the shallow and deep aquifers, as seen with arsenic. Concentrations are highest in the Holocene aquifers from Rajshahi–Pabna area (Ganges, Atrai Floodplains) the Jamuna Valley and the eastern part of the Tista Fan (Young Gravelly Sand Unit of Alam et al., 1990). The high concentrations are believed to reflect the distribution of groundwaters which are less reducing than those found in the lower parts of the Bengal delta. The spatial distribution of manganese differs from that of iron and arsenic.

Maps are also given of the distribution of manganese concentrations based on health-related class boundaries and also on the relationships between manganese and arsenic. The WHO health-based guideline value for manganese is 0.5 mg L$^{-1}$. 35% of groundwater samples collected in the survey exceeded this value. The smoothed map for manganese shows a distinctly different pattern from arsenic and iron. The arsenic vs manganese map highlights the spatial differences between the two elements.
Arsenic contamination of groundwater in Bangladesh

Manganese
(health) (mg L\(^{-1}\))
- <0.1
- 0.1–0.5
- 0.5–1
- >1

'Groundwater Studies of Arsenic Contamination in Bangladesh'
DPHE/BGS/DFID (2000)
Manganese (mg L$^{-1}$)

- <0.18
- 0.18–0.28
- 0.28–0.36
- 0.36–0.44
- 0.44–0.5
- 0.5–0.6
- 0.6–0.7
- 0.7–0.9
- 0.9–1.2
- >1.2

'Groundwater Studies of Arsenic Contamination in Bangladesh'
DPHE/BGS/DFID (2000)
Phosphorus Concentrations of phosphorus range between <0.1 mg L\(^{-1}\) and 19 mg L\(^{-1}\) in the shallow groundwaters and between <0.1 mg L\(^{-1}\) and 6.1 mg L\(^{-1}\) in the deep groundwaters. Median concentrations in each are 0.29 mg L\(^{-1}\) and 0.33 mg L\(^{-1}\) respectively. These concentrations are relatively high compared to average groundwater compositions.

The map shows that highest concentrations (>1 mg L\(^{-1}\)) are mainly found in south-eastern and north-eastern Bangladesh and along the Jamuna Valley. The distribution shows many similarities with that of arsenic, although in contrast to arsenic, many of the deep groundwaters of Barisal have relatively high concentrations (often >1 mg L\(^{-1}\) P). The phosphorus is believed to derive by desorption from iron oxides and from organic matter. Dissolution of detrital apatite from sediments is also a likely contributor. The prevalence of high concentrations even in the deep groundwaters (>150 m) precludes fertilisers as a major source.

Dissolved phosphate is likely to compete with dissolved arsenic species (arsenite, arsenate) for adsorption sites on iron and other oxides and the high observed phosphorus concentrations may be an additional factor in the mechanism of arsenic mobilisation in the Bangladesh groundwaters. However, the presence of high phosphorus concentrations in many of the deep groundwaters with low arsenic concentrations indicate that this may be only one of a number of factors involved in arsenic release.
Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/DFID (2000)
Potassium

Concentrations of potassium have a comparable range in the shallow and deep groundwaters of Bangladesh, with ranges of between $<0.6 \text{ mg L}^{-1}$ and $4.0 \text{ mg L}^{-1}$ in the shallow groundwaters and between and $<0.6 \text{ mg L}^{-1}$ and $3.8 \text{ mg L}^{-1}$ in the deep groundwaters. Median values are slightly higher in the deep aquifers (shallow and deep being $2.2 \text{ mg L}^{-1}$ and $3.3 \text{ mg L}^{-1}$ respectively). Concentrations in the deep groundwaters of Barisal are often high, though variable.

The map shows that the highest potassium concentrations occur in the south-east of Bangladesh with some relatively high concentrations in the groundwaters from the Jamuna Valley. Derivation of potassium is believed to be largely by mineral reactions in the aquifers, principally deriving from clay minerals and from weathering of micas. The distribution likely reflects the relative abundance of clay minerals in the southern part of the delta where deposits are more typically fine-grained.
"Groundwater Studies of Arsenic Contamination in Bangladesh"
DPHE/BGS/DFID (2000)
Concentrations of silicon in Bangladesh groundwaters are commonly high, the ranges in the shallow and deep groundwaters being $<10–21 \text{ mg L}^{-1}$ and $2–16 \text{ mg L}^{-1}$ respectively. Median values are $20 \text{ mg L}^{-1}$ and $13 \text{ mg L}^{-1}$ respectively. Maximum concentrations are likely to be limited by solubility with silicate minerals (quartz, cristobalite, amorphous silica).

The regional distribution of silicon shows that highest concentrations are generally found in groundwaters from the Barind and Madhupur Tracts and the western part of the Tista Fan. Sporadic highs also occur in south-east Bangladesh. The highest observed concentrations ($>30 \text{ mg L}^{-1}$) are found in the majority of samples from the Madhupur Tract, from the northern part of the Barind Tract and in the south-east border region with Tripura. The high concentrations are believed to reflect more enhanced reaction of silicate minerals as a result of long groundwater residence times in the aquifers.

Relatively low concentrations ($<16 \text{ mg L}^{-1}$) have been found in the deep groundwaters from southern Bangladesh (Barisal region) and from the Sylhet Basin. The reason for this is not clear.
Silicon (mg L\(^{-1}\))

- <16
- 16–20
- 20–25
- >25

'Groundwater Studies of Arsenic Contamination in Bangladesh'
DPHE/BGS/DFID (2000)
SODIUM

Concentrations of sodium vary between 0.7 mg L\(^{-1}\) and 73 mg L\(^{-1}\) in the shallow groundwaters and between 2.5 mg L\(^{-1}\) and 251 mg L\(^{-1}\) in the deep groundwaters. Concentrations are overall greater in the deep groundwaters, but this is because a large proportion of these were collected from the Barisal region of southern (coastal) Bangladesh, as well as from Sylhet area.

The map shows the highest sodium concentrations are mainly found in the south and south-eastern parts of Bangladesh and in the low-lying hoar region of the north-east (Figure 1.x). High concentrations reflect past inundation of the delta by seawater and past (and possibly present) episodes of saline intrusion in response to variations in relative sea level. Following the last glacial period, rising sea levels resulted in marine inundation of these areas between around 6500–4000 years ago. Relatively low sodium concentrations are found in the comparatively high ground of the Madhupur and Barind Tracts, the Sylhet Hills (Dihing and Dupi Tila outcrops) on the eastern border and the Tista Fan region in the north, as well as along the Jamuna Valley.
Sodium (mg L\(^{-1}\))
- <13
- 13–26
- 26–70
- >70

Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/DFID (2000)
Strontium

Concentrations of strontium range between <0.2 mg L\(^{-1}\) and 1.6 mg L\(^{-1}\) in the shallow groundwaters and between <0.2 mg L\(^{-1}\) and 3 mg L\(^{-1}\) in the deep groundwaters. Strontium is likely to be derived dominantly from reaction with carbonate minerals, although mixing with saline waters is likely in the areas affected by past or present saline intrusion (seawater has a strontium concentration of around 8 mg L\(^{-1}\)). Relatively high concentrations in the deep groundwaters probably reflect this increased salinity, especially those from the coastal area.

The regional distribution of strontium in the groundwaters to a large extent resembles that of calcium and magnesium and, as with these elements, reflects dissolution of carbonate minerals in the sediments and soils. Some high concentrations in the south are also likely due to saline influences. Lowest concentrations are found in groundwaters from the Tista Fan and from the Sylhet Basin. Low concentrations are also found in the deep groundwaters of the extreme south (coastal) part of Bangladesh, in line with the low calcium concentrations.
Strontium (mg L$^{-1}$)

- $<0.09$
- 0.09–0.18
- 0.18–0.34
- $>0.34$

‘Groundwater Studies of Arsenic Contamination in Bangladesh’
DPHE/BGS/DFID (2000)
SULPHATE

Concentrations of sulphate in groundwaters from the National Hydrochemical Survey range between <0.2 mg L$^{-1}$ and 753 mg L$^{-1}$ in the shallow groundwaters and between <0.2 mg L$^{-1}$ and 96 mg L$^{-1}$ in the deep groundwaters. Sulphate concentrations are mainly very low in the Bangladesh groundwaters, the median values in both the shallow and deep groundwaters being <1 mg L$^{-1}$. The map of sulphate distribution shows that concentrations are generally lowest in the south-west and southern parts as well as in north-eastern Bangladesh. The deep groundwaters of Barisal also have mostly low concentrations (<4 mg L$^{-1}$). Concentrations are typically higher (>4 mg L$^{-1}$) in the north, particularly in groundwaters from the Tista Fan, the Jamuna Valley and the Rajshahi–Pabna area (Ganges and Atrai Floodplains).

The low concentrations of sulphate (around 1 mg L$^{-1}$ or less) occur under strongly reducing conditions and often occur in areas affected by residual seawater (southern Bangladesh, Sylhet Basin) which would be expected to have increase sulphate concentrations as a result of the high values found in seawater (around 2700 mg L$^{-1}$). The low concentrations suggest that bacterial sulphate reduction has occurred. Supporting evidence for the process of sulphate reduction in the aquifers comes from enriched sulphur-34 isotopic compositions in a limited number of groundwater samples from the Special Study Areas, and in the more saline groundwaters of Lakshmipur upazila, low SO$_4$/Cl ratios relative to seawater, indicating sulphate loss from solution. Sulphate reduction appears to have been an important process in both the shallow and deep aquifers.

The sulphate map shows that higher concentrations are found in shallow groundwaters from the northern Ganges Floodplain, The Jamuna Valley and the Tista Fan aquifers and from parts of the Barind Tract (although Madhupur Tract groundwaters appear to have low concentrations, of typically <1 mg L$^{-1}$). These are considered to be more oxidising groundwaters than those in the lower parts of the delta. The sulphate present may either be derived from recharge (following concentration by evapotranspiration), or surface pollution (many of the groundwaters from the Jamuna Valley in particular are abstracted from shallow depths), or derived from oxidation of sulphide minerals (pyrite) in the aquifers. These processes are difficult to distinguish in practice. In any case, if the relatively high sulphate concentrations are derived by oxidation of pyrite, this appears not to be a mechanism for arsenic release into the groundwaters as these high-sulphate waters have typically low arsenic concentrations. In the Jamuna Valley where high arsenic concentrations exists, these are generally in low-sulphate groundwaters (Main Report, Chapter National Hydrochemical Survey).
The National Hydrochemical Survey

80° 89° 90° 91° 92° 93°

Sulphate (mg L$^{-1}$)
- <0.2
- 0.2–0.8
- 0.8–4
- >4

Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/DFID (2000)
ARSENIC AND IRON

Most Bangladesh groundwaters have high concentrations of both Fe and As by world standards, and it is often found that these two elements can be strongly correlated, although this is by no means always the case. Indeed, on a well-by-well basis, the Fe concentration in a well water generally provides a poor predictor of the As concentration. Nevertheless, it is clear that iron oxides are closely associated with the development of high As groundwaters in Bangladesh, and the ratio can be informative. In particular, simple reductive dissolution would predict a strong relationship and, all other things being equal, should give a relatively constant As/Fe ratio.

The observed ratio, As/Fe (plotted in terms of its logarithm) shows some clear spatial trends with the highest ratios tending to be found in the areas with high absolute As concentrations.
Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/DFID (2000)

Bay of Bengal
India

log As/Fe (molar)
- < -3
- -3 to -2.4
- -2.4 to -1.8
- > -1.8
ARSENIC AND MANGANESE

Many groundwaters from north-western Bangladesh in particular have low arsenic but high manganese concentrations. The survey showed that 8% of samples exceeded both 50 µg L\textsuperscript{-1} arsenic and 0.5 mg L\textsuperscript{-1} manganese, while 48% of samples were below both these criteria. Altogether, 36% of samples which had arsenic below 50 µg L\textsuperscript{-1} had manganese concentrations above 0.5 mg L\textsuperscript{-1}. Groundwater from the Barind and Madhupur Tracts, the deep aquifer in southern coastal Bangladesh and Sylhet (and Dhaka) and from the coarser sediments of north-western Bangladesh tended to comply on both counts.
Arsenic vs Manganese

As (µg L\(^{-1}\)) Mn (mg L\(^{-1}\))

- <50 <0.5
- <50 >0.5
- >50 <0.5
- >50 >0.5

‘Groundwater Studies of Arsenic Contamination in Bangladesh’
DPHE/BGS/DFID (2000)
IRON AND MANGANESE

Bangladesh groundwaters have unusually high concentrations of both Fe and Mn by world standards. This reflects the highly reducing nature of the groundwaters and probably the presence of relatively high concentrations of poorly ordered oxides, and therefore rather soluble oxides, in the very young the sediments of the delta region.

While Fe and Mn both dissolve under reducing conditions, their chemistries are significantly different with Mn oxides tending to dissolve before Fe oxides as groundwaters become progressively more reducing. This is dictated by their relative positions in the standard redox sequence as well as kinetic factors. This means that there is often some separation between Fe and Mn in the environment. This appears to be the case with a large and systematic variation in the Mn/Fe ratio.
Mn/Fe (molar)

- <0.05
- 0.05–0.2
- 0.2–1
- >1

'Groundwater Studies of Arsenic Contamination in Bangladesh'
DPHE/BGS/DFID (2000)
MAGNESIUM AND CALCIUM

As noted in the individual element maps, there is a marked north-south divide in the hardness of waters with high Mg and Ca waters being particularly associated with Ganges sediments. The ratio Mg/Ca reflects this as well as possible differences in the sources of the two elements, especially the role of the carbonates, calcite (Ca) and dolomite (Ca and Mg).
Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/DFID (2000)
SODIUM AND POTASSIUM

The K/Na ratio shows both the influence of saline intrusion, which gives a low ratio in southern Bangladesh due to high salinity, and the weathering of minerals such as feldspars and micas, in the sandy sediments (relatively high K and low Na in northern Bangladesh).
K/Na (molar)

- <0.04
- 0.04–0.1
- 0.1–0.25
- >0.25

'Groundwater Studies of Arsenic Contamination in Bangladesh'
DPHE/BGS/DFID (2000)
REFERENCE

2 The BWDB Water-Quality Monitoring Network

INTRODUCTION

A survey of groundwater quality has also been carried out from the 113 tubewells in the BWDB Water-Quality Monitoring Network. This is a national network with sites located in all districts except the three districts of the Chittagong Hill Tracts and Sunamganj in the north-east. The tubewells in the network are monitored approximately bi-annually by BWDB for water levels and a range of other chemical constituents. The survey was carried out during May–July 1998, except for 11 samples from the north-east which were collected in June 1999 due to accessibility problems in 1998.

At the time of planning the 1998 survey, it was not clear that the more complete survey of northern Bangladesh would go ahead and so this rather limited BWDB network provided an indication of the likely range of water quality to be found over the whole of Bangladesh. A number of minor elements not previously analysed by BWDB or DPHE were included in the suite of elements that were analysed.

A discussion of the data is given in Chapter 6 (The National Hydrochemical Survey) of the Main Report.

SITE DETAILS
WATER-QUALITY PARAMETERS

Arsenic ($\mu$g L$^{-1}$)
- $<0.5$
- $0.5-4$
- $4-50$
- $>50$

Barium (health) (mg L$^{-1}$)
- $<0.3$
- $0.3-0.5$
- $0.5-0.7$
- $>0.7$

Barium (mg L$^{-1}$)
- $<0.03$
- $0.03-0.06$
- $0.06-0.12$
- $>0.12$

Boron (mg L$^{-1}$)
- $<0.02$
- $0.02-0.04$
- $0.04-0.1$
- $>0.1$
*Groundwater Studies of Arsenic Contamination in Bangladesh*
DPHE/BGS/BWDB/DFID (2000)
Fluoride (mg L$^{-1}$)

- $<$0.12
- 0.12--0.21
- 0.21--0.32
- $>$0.32

Iodide (mg L$^{-1}$)

- $<$0.003
- 0.003--0.014
- 0.014--0.05
- $>$0.05

Iodide (health) (mg L$^{-1}$)

- $<$0.002
- 0.002--0.005
- 0.005--0.01
- $>$0.01

Iron (mg L$^{-1}$)

- $<$0.15
- 0.15--1
- 1--5
- $>$5

"Groundwater Studies of Arsenic Contamination in Bangladesh"
DPHE/BGS/BWDB/DFID (2000)
Arsenic contamination of groundwater in Bangladesh

Manganese (health) (mg L⁻¹)
- <0.1
- 0.1–0.5
- 0.5–1
- >1

Phosphorus (mg L⁻¹)
- <0.1
- 0.1–0.3
- 0.3–1
- >1

Nickel (μg L⁻¹)
- <1
- 1–2
- 2–4
- >4

Potassium (mg L⁻¹)
- <1.5
- 1.5–3
- 3–5
- >5

*Groundwater Studies of Arsenic Contamination in Bangladesh*
DPHE/BGS/BWDB/DFID (2000)

Bay of Bengal
India

200 km
Sodium (mg L$^{-1}$)
- $<13$
- 13–26
- 26–70
- $>70$

Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/BWDB/DFID (2000)

Bay of Bengal
India
200 km

Sulphate (mg L$^{-1}$)
- $<0.2$
- 0.2–0.8
- 0.8–4
- $>4$

Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/BWDB/DFID (2000)

Bay of Bengal
India
200 km

Strontium (mg L$^{-1}$)
- $<0.09$
- 0.09–0.18
- 0.18–0.34
- $>0.34$

Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/BWDB/DFID (2000)

Bay of Bengal
India
200 km

Uranium (µg L$^{-1}$)
- $<0.05$
- 0.05–0.5
- 0.5–2
- $>2$

Groundwater Studies of Arsenic Contamination in Bangladesh
DPHE/BGS/BWDB/DFID (2000)

Bay of Bengal
India
200 km
3 Special Study Areas

INTRODUCTION

Chemical data collected for groundwaters from the National Hydrochemical Survey give useful information about the inorganic groundwater quality and the regional variations but interpretation is limited by the range of determinands analysed. More detailed analysis of the national survey samples, including anion, trace-element and isotopic analysis, was beyond the scope of the project. However, these parameters are of great potential value in assessing hydrogeochemical processes in the aquifers and for this reason, three Special Study Areas were chosen in which to carry out more detailed groundwater chemical analysis. These study areas were also the focus of mineralogical and sediment chemistry investigations, groundwater monitoring and flow modelling. The areas chosen were the headquarter (sadat) upazilas of the Districts of Lakshmipur, Faridpur and Nawabganj. Samples were also collected from Shibganj, the neighbouring upazila to Chapai Nawabganj headquarter upazila (Nawabganj District) and Chatkhil (neighbouring upazila to Lakshmipur headquarter upazila). The areas were selected as they have recognised arsenic problems, are distributed widely across the alluvial and deltaic plain of Bangladesh in different sections of the Bengal drainage system and have differing geological and hydrogeological characteristics.

Details of the sampling and analytical methods and a discussion of the data are given in Chapter 7 (Hydrogeochemistry of three Special Study Areas) of the Main Report.
LOCATION OF SPECIAL STUDY AREAS

'Special Study Areas'

Chapai Nawabganj
Faridpur
Lakshmipur

'Groundwater Studies of Arsenic Contamination in Bangladesh'
BGS/DPHE/DFID (2000)
Sample ID’s

'Groundwater Studies of Arsenic Contamination in Bangladesh'
BGS/DPHE/DFID (2000)
Geology

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
DEPTH OF WELLS

"Groundwater Studies of Arsenic Contamination in Bangladesh"
BGS/DPHE/DFID (2000)
ALKALINITY

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
AMMONIUM

NH₄-N mg L⁻¹

- <0.05
- 0.05-0.4
- 0.4-1.5
- >1.5

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
ARSENIC (TOTAL)

'Groundwater Studies of Arsenic Contamination in Bangladesh'
BGS/DPHE/DFID (2000)
**ARSENIC (As(III))**

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
Barium contamination of groundwater in Bangladesh

**Barium**

![Map of Bangladesh with Barium contamination levels](image)

**Ba µg L⁻¹**
- <50
- 50-110
- 110-170
- >170

Map showing contamination levels and locations in Bangladesh:
- ** Nawabganj and Shibganj**
- ** Chapai Nawabganj town**
- **Faridpur**
- **Lakshmipur**

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*Groundwater Studies of Arsenic Contamination in Bangladesh*
BGS/DPHE/DFID (2000)
Boron

"Groundwater Studies of Arsenic Contamination in Bangladesh"
BGS/DPHE/DFID (2000)
Bromide

BGS/DPHE/DFID (2000)
’Groundwater Studies of Arsenic Contamination in Bangladesh’
'Groundwater Studies of Arsenic Contamination in Bangladesh'
BGS/DPHE/DFID (2000)
CHLORIDE

'Groundwater Studies of Arsenic Contamination in Bangladesh'
BGS/DPHE/DFID (2000)


**Dissolved Organic Carbon**

DOC (mg L⁻¹)

- <1
- 1-2
- 2-3
- >3

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
Dissolved oxygen

"Groundwater Studies of Arsenic Contamination in Bangladesh"
BGS/DPHE/DFID (2000)
**Fluoride**

Groundwater Studies of Arsenic Contamination in Bangladesh

BGS/DPHE/DFID (2000)
Iodide

'Groundwater Studies of Arsenic Contamination in Bangladesh'
BGS/DPHE/DFID (2000)
IRON

Fe mg L⁻¹
- <0.3
- 0.3-1.5
- 1.5-5.0
- >5.0

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
LEAD

\[ \begin{array}{c|c|c|c|c|c}
\text{Pb} \mu g L^{-1} & <0.05 & 0.05-0.1 & 0.1-0.2 & >0.2 \\
\hline
\end{array} \]

\text{Shibganj}

\text{Nawabganj}

\text{Ganges}

\text{Mahananda}

\text{INDIA}

\text{BANGLADESH}

\text{Purba Fargilpur}

\text{Chapai Nawabganj town}

\text{Chanlai}

\text{Shibganj}

\text{Rajarampur}

\text{Baragharia}

\text{R. Ganges}

\text{R. Meghna}

\text{Chatkhil}

\text{Ramganj}

\text{Lakshmipur}

\text{R. Mahananda}

\text{Chakhal}

\text{Faridpur}

\text{FARIDPUR}

\text{LAKSHMIPUR}

\text{NOAKHALI}

\text{LAKSHMIPUR}

\text{RAIPUR}

\text{R. Meghna}

\text{Faridpur}

\text{R. Ganges}

\text{Shibganj}

\text{Nawabganj}

\text{BAGDAD CHORD}

\text{'Groundwater Studies of Arsenic Contamination in Bangladesh'}

BGS/DPHE/DFID (2000)
LITHIUM

![Map of Lithium Distribution in Bangladesh]

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
Magnesium

![Magnesium map of Bangladesh](image)

"Groundwater Studies of Arsenic Contamination in Bangladesh"
BGS/DPHE/DFID (2000)
MANGANESE

\[\text{Mn } \text{mg L}^{-1}\]

- <0.2
- 0.2-0.5
- 0.5-1.0
- >1.0

*Groundwater Studies of Arsenic Contamination in Bangladesh*
BGS/DPHE/DFID (2000)
Molybdenum

"Groundwater Studies of Arsenic Contamination in Bangladesh"
BGS/DPHE/DFID (2000)
GROUNDWATER STUDIES OF ARSENIC CONTAMINATION IN BANGLADESH

BGS/DPHE/DFID (2000)
**Nitrate**

NO$_3$-N mg L$^{-1}$
- <1
- 1-10
- >10

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
PH

'Groundwater Studies of Arsenic Contamination in Bangladesh'
BGS/DPHE/DFID (2000)
Arsenic contamination of groundwater in Bangladesh

**Phosphorus**

> **Groundwater Studies of Arsenic Contamination in Bangladesh**
> BGS/DPHE/DFID (2000)
Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
Arsenic contamination of groundwater in Bangladesh

**REDOX POTENTIAL**

![Diagram showing the redox potential of groundwater in Bangladesh with color-coded regions indicating different Eh values.]

- **Eh mV**
  - <40
  - 40-80
  - 80-120
  - >120

'Groundwater Studies of Arsenic Contamination in Bangladesh'
BGS/DPHE/DFID (2000)
RUBIDIUM

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
Silicon contamination of groundwater in Bangladesh

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
Special Study Areas

SODIUM

Na mg L$^{-1}$
- <15
- 15-30
- 30-60
- >60

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
SPECIFIC ELECTRICAL CONDUCTANCE

 SEC $\mu$S cm$^{-1}$

- >500
- 500-750
- 750-1000
- 1000

"Groundwater Studies of Arsenic Contamination in Bangladesh"
BGS/DPHE/DFID (2000)
STRONTIUM

Sr $\mu$g L$^{-1}$
- <250
- 250-350
- 350-450
- >450

Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
SULPHATE

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Groundwater Studies of Arsenic Contamination in Bangladesh
BGS/DPHE/DFID (2000)
HYDROGEN ($^{2}H/^{1}H$)

$\delta^{2}H^{\circ}$

- $<-37$
- $-37$ to $-29$
- $-29$ to $-22$
- $> -22$

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OXYGEN ($^{18}\text{O}/^{16}\text{O}$)

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4 A village survey: Mandari, Lakshmipur

A rapid hydrochemical survey of the mouza (village) of Mandari, Lakshmipur District was carried out during November 1999.

Arsenic in the survey was measured in a various field ‘laboratories’ using an Arsenator developed and operated by Professor Walter Kosmus of Karl-Franzens University of Graz, Austria.

The shallow wells in Mandari are at a fairly uniform depth — mostly in the range 30–36 ft (9–11 m). Additional analyses were also carried out on acidified samples by ICP-AES as with the other surveys. A discussion of the data is given in Chapter 8 A village survey: Mandari, Lakshmipur District of the Main Report.

SAMPLE POINTS
**Depth of Well**

**Aluminium**
ARSENIC

ARSENIC (CLOSE-UP)

Posted values are arsenic concentrations in \( \mu g \) L\(^{-1}\).
**Arsenic contamination of groundwater in Bangladesh**

### Boron

![Boron Map]

### Barium

![Barium Map]
**CALCIUM**

**IRON**
MAGNESIUM

MANGANESE
**Phosphorus**

![Phosphorus Map]

**Potassium**

![Potassium Map]
Silicon

Sodium