6 The National Hydrochemical Survey

6.1 INTRODUCTION

There have been various surveys of water quality in Bangladesh. Each of these have had different objectives, regional coverages, sample densities and determinand suites. Until around 1997, no surveys included arsenic as one of the measured elements. Most also did not include accurate geo-referencing of sampling points making mapping difficult. Nonetheless, the various surveys provided useful data that gave a broad indication of the major element groundwater quality in Bangladesh.

Since the alarm was first raised in Bangladesh about excessive arsenic concentrations in groundwater in the mid 1990's, there have been a number of arsenic surveys in Bangladesh. However, none of these was sufficiently comprehensive or had a sufficient dense sample density to give a reliable national picture of groundwater quality. This chapter gives an account of the results from the DPHE/BGS National Hydrochemical Survey (NHS) carried out within this project. This has provided the first comprehensive groundwater quality survey of Bangladesh. Where appropriate, we compare our results with earlier surveys.

6.2 EARLIER WATER-QUALITY SURVEYS

Halcrow and DHV (1995) carried out a survey of baseline groundwater quality in Bangladesh, concentrating particularly on heavily cropped areas of the country and the effects of pesticide and fertiliser use. They concluded from the 78 groundwater samples collected that, apart from coastal areas, groundwater was fresh and 'generally suitable for drinking … and irrigation'. Ionic charge balances for most samples were however poor and so the major-element results are considered with caution. Halcrow and DHV (1995) identified high concentrations of iron and ammonium in many samples, high phosphorus in some and uniformly low fluoride concentrations (≤0.8 mg L^{-1}). They also found that most were not contaminated with pesticide residues, although low concentrations of DDT and heptachlor (up to 1.5 μg L^{-1} and 1.02 μg L^{-1}, respectively) were detected in a few samples. Arsenic was not measured in the survey.

Davies (1994) investigated groundwater quality in the Dhamrai area of north-central Bangladesh, covering part of the Jamuna Valley (Holocene alluvium) and the Madhupur Tract (Dupi Tila Formation). Differences were identifiable between groundwaters from the two aquifers, with higher HCO_3, Mn, Ca, Mg, K concentrations and some high phosphorus concentrations in the former. Arsenic was not measured in the survey. Indeed, the Jamuna Valley was not recognised as a problem area with respect to arsenic until a few years later (DPHE/UNICEF field-test kit and DCH/SOES surveys).

NRECA (1997) surveyed around 570 tubewells for arsenic and ferrous iron as well as a subset for other determinands including dissolved oxygen, phosphate, sulphate and chloride. Sample sites were in clusters spaced about 25–50 km apart and spread around the country. The survey identified the highest average arsenic concentrations in Chandpur, Faridpur and Feni. Arsenic was also identified (>50 μg L^{-1}) in isolated pockets west of Rajshahi and in Bhola, Bogra, Phulbar, Kishoreganj, Jamalpur and east of Sylhet. Redox potentials were found to be highest in northern Bangladesh, especially the Madhupur and Barind Tracts and the Tista fan area. Spatial distributions of iron were variable but salinity indicators and phosphate were generally higher in the coastal area. They concluded that in general, high arsenic concentrations correlated with low redox potential, electrical conductance greater than 700 μS cm^{-1}, low dissolved oxygen, total iron above 10 mg L^{-1}, phosphate (as PO_4) above 4.5 mg L^{-1} and chloride above 25 mg L^{-1}. They found low SO_4 concentrations (typically 1–2 mg L^{-1} or less) in groundwater from almost all areas.

BUET analysed around 1200 samples from irrigation wells in north-east Bangladesh for arsenic using the SDDC method. They found around 33% exceeded the Bangladesh standard for arsenic and 60% exceeded the WHO guideline value. The worst-affected districts appeared to be Moulvibazar and Sunamganj.

DCH/SOES have reportedly carried out extensive surveys of arsenic in around 22,000 wells across Bangladesh over the last five years (e.g. DCH, 1997; SOES/DCH, 2000). Their surveys have identified severe arsenic contamination in many areas, including northern Bangladesh and the group have reported contamination in 43 out of 64 districts in Bangladesh. The affected populations were estimated to be 51 million drinking water with >10 μg L^{-1} and 25 million drinking water with >50 μg L^{-1} As. Their well-selection strategy is not clear and much of the sampling appears to have been governed by the location of patients with arsenic-related health problems. In this sense, the sampling is likely to have been biased rather than randomised and may therefore be an overestimate.

In addition to these large-scale surveys, more localised water-quality investigations have been carried out at various times by a number of organisations. Nickson (1997) collected around 30 groundwater samples from various locations in the Holocene alluvial aquifer and 17 from Dhaka deep wells. High concentrations of iron, manganese and bicarbonate and often low nitrate and sulphate concentrations were found in the groundwaters from the Holocene aquifers. Dhaka deep wells had uniformly low arsenic concentrations (<0.1–2 μg L^{-1}) as well as much lower iron, manganese and bicarbonate.

Safiullah (1998) analysed over 500 samples in Faridpur Municipality and reported that around 70% of the samples collected were contaminated with arsenic (i.e. >50 μg L^{-1})

and displayed considerable spatial variability. Lack of correlation between dissolved arsenic and iron was also noted. Various other local arsenic investigations have also been carried out by DANIDA, BWDB, Rajshahi University and the Asian Arsenic Network (AAN).

Since the instigation of the National Hydrochemical Survey, a number of other more recent local groundwater investigations have been carried out, including studies by Harvard University, USA, USGS/Geological Survey of Bangladesh, AAN and various MSc students. Large-scale arsenic surveys have also been carried out by NIPSOM-UNDP, DPHE-UNICEF and BAMWSP. Comparison between these larger surveys and the National Hydrochemical Survey is given in Section 6.15.

6.3 Aims of the National Hydrochemical Survey

In light of the patchiness of previously existing (pre-1998) analyses of arsenic and other elements, common lack of geo-referencing, the limitations of field-test kits and sometimes bias in choice of sampling locations for whatever reason, a national survey of arsenic and a range of other diagnostic elements in the groundwaters was carried out during this project. The aims of the survey were: (i) to produce maps showing the regional distribution of arsenic and other elements in the groundwaters and (ii) to provide estimates of the percentage of wells exceeding various limits for arsenic and other elements.

Production of maps is relatively straightforward, but obtaining unbiased statistics is much more demanding. When the survey was originally planned, it was thought that there were some 2–3 million tubewells in Bangladesh and so it was obvious that only a small proportion of all available wells could be sampled. Our original intention was that 1500–2500 wells should be sampled from what were then (early 1998) thought to be the worst-affected areas. This translated to about 8 samples per *upazila* since there were about 250 *upazilas* in the chosen area. The earlier extensive arsenic survey of well waters by DPHE staff using field-test kits was used for selecting what were then believed to be the worst-affected districts.

The ideal sought was for some form of randomised sampling but this was difficult to achieve for various reasons: (i) there was no register of available wells or even maps of their locations; (ii) there was no local experience of carrying out randomised surveys (or even an appreciation of their importance); (iii) the sampling had to be carried out quite rapidly which meant that most wells had to be close to a road, and (iv) we wanted to have reliable data for the date of construction of the well and its depth and so the majority of wells selected were government-constructed (DPHE) wells. There are not believed to be any systematic differences between Government and private wells in Bangladesh in part because the same drillers are often involved. The depth of wells in a given area is largely governed by the so-called 'depth book' which is kept in the local DPHE *upazila* office. This reassurance was of critical importance in selecting predominantly DPHE-constructed wells for the regional survey.

Apart from the above points, every attempt was made to ensure that the sampling strategy was as close to being random as possible. In particular, no knowledge of the arsenic concentration of the wells was used when selecting wells. We also wanted the spatial coverage to be as uniform as possible and we therefore attempted to stratify spatially.

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). The CHTs were excluded because their sediments were thought to not give rise to high arsenic groundwaters, groundwater is used less in the area and existing wells are relatively sparse and often have difficult access. Including the CHTs at this stage would have detracted from what were known to be areas of higher priority elsewhere and we were well aware that our chosen sample density was in any case low in relation to the likely scales of variation.

A collaborative microbiological study of the tubewell water quality was carried out by Hoque (1998) during the 1998 (southern) survey. Samples were rapidly transported to the ICDDR,B laboratory in Dhaka for faecal coliform and ammonia analysis.

6.4 Survey methodology

6.4.1 Site selection and sampling

Details of the planning and organisation of the sampling are described in detail in the Phase I report (DPHE/BGS/MML, 1999). A similar approach was adopted for the second phase of sampling. Briefly, the sampling was organised on a district and *upazila* basis. At any one time, there were up to five active sampling teams (two for the second phase of sampling) and a timetable was devised on the basis that each team would sample one *upazila* per day. Sampling was completed district-wise. DPHE is organised regionally and there are five main DPHE Circles. A meeting of all DPHE Executive Engineers (XENs) for a given DPHE Circle was held at the office of the Circle Superintending Engineer at the start of the survey. The Project Director and Team Leader or Deputy Team Leader outlined the aims of the survey and the approach to be adopted. A sampling timetable for the Circle was agreed. A week or two prior to the sampling, the XEN would organise a meeting between the Team Leader and the local DPHE Sub Assistant Engineers (SAEs) to outline the aims of the survey and the sampling strategy. The desired 'randomness' of the survey was emphasised ('we are looking for high arsenic areas, medium arsenic areas and low arsenic areas, i.e. we want to sample everywhere as uniformly as possible'). The SAEs would then prepare a list of wells to be sampled. The XEN would also make local arrangements for accommodation for the sample team.

Each sample team consisted of a sampler (either a junior Hydrogeologist from DPHE R&D Division or a graduate from the Geology Department of Dhaka University recruited for the project), a local DPHE SAE as guide and helper, and a driver. Each team also had a four-wheel drive vehicle for transport and in most cases, a hand-held GPS for locating the wells. Some wells from Rajshahi and Nawabganj districts were sampled without access to a GPS

and so their locations were estimated from the 1:50,000 LGED *upazila* maps.

Well selection was made using the following strategy: (i) a 3 × 3 grid was pencilled on the *upazila* map to divide the *upazila* into approximately nine equal-area cells; (ii) a route was planned between the cells; (iii) at least one well was selected from each cell ensuring that there was at least 2 km between samples from adjacent wells – normally about 10–12 wells were initially selected by the SAEs in this way; (iv) the final selection of the wells was made by the sampling team leader while on the road. Normally one or two were dropped from the initial list. Preference was given to DPHE-constructed wells.

In a few instances, strong pressure was brought upon the sample team leader to sample more than the required number of wells. Normally this was resisted but in a couple of cases, extra samples were taken, e.g. in the Khulna area. A note was taken of the extra wells selected. A retrospective analysis of these samples suggested that the extra wells were not significantly different from the original set and so they have been retained in the final data set.

In most of Bangladesh, the wells are predominantly in the shallow aquifer – usually in the range 15–70 m depth. Enquiries were also made about the existence of 'deep' wells in the area and where possible extra samples were taken from these even if they were close to a sampled shallow well. In practice, the number of deep wells in existence was small outside of the southern coastal area, affected by salinity and the north-east region, where the shallow aquifer is sometimes poor. Details of each well were recorded on a proforma during the visit. A total of 326 samples were collected from the deep aquifers.

Most of the wells sampled were fitted with a standard Bangladesh number 6 hand pump. Each well was purged prior to sampling by pumping one stroke per foot of well depth. The water was filtered through a 0.2 μm Millipore filter into a plastic 30 ml Sterilin tube and acidified with 'a few drops' (instructions were 10 drops) of concentrated Analytical Grade nitric acid. Nitric acid was used so that the samples could if necessary be analysed by ICP-MS (chloride from hydrochloric acid would interfere with the arsenic determination). Samples were periodically air-freighted to the UK and stored there at 5°C before and after analysis.

Upazila names were based on the 1991 census names with a few more recent amendments. This gave a total of 496 *upazilas* in Bangladesh. Many of the thirty or so new *upazilas* since the 1981 census have arisen from the subdivision of the larger metropolitan areas.

6.4.2 Analytical procedures

Details of the analytical procedures are given in the Phase I report. The initial aim of the project was for all of the arsenic analyses to be carried out in one of the four DPHE Zonal laboratories using 250 ml samples and for a 1:10 check to be made with the BGS laboratories. Separate, smaller acidified samples were collected for this. All samples were duplicated in this way and shipped to the UK as a contingency.

In the event, the DPHE results proved to be insufficiently reliable and so all Phase I samples were eventually reanalysed in the UK. The reasons for the problems with the DPHE results were never completely resolved but were probably in part due to poor sample preservation (not enough acid added for the volume of sample taken) and in part due to poor laboratory procedures. A number of recommendations for improving the DPHE procedures were made in the Phase I report and many of these have since been adopted, in part with UNICEF assistance. For example, the laboratories are now converting to a borohydride method for arsenic analysis which should overcome the problem of obtaining high-quality zinc.

Most of the samples were analysed for arsenic by hydride generation-atomic fluorescence spectrometry (HG-AFS) but some of the early samples collected in the Phase I survey were analysed by hydride generation-ICP-AES. Agreement between the two methods was good. The detection limit for the AFS determination was generally 0.25 or 0.5 $\mu g\ L^{-1}$ (depending on the calibration range chosen) whereas for the HG-ICP-AES method it was about 6 $g\ L^{-1}$ (6σ).

Additional elements were measured on the survey samples by ICP-AES and in a few cases by ICP-MS. Further details of ICP-AES and ICP-MS analytical procedures are given in Chapter 7. As with the samples from the Special Study Areas, the NHS samples were periodically interspersed with standard reference materials. Average results for 60 determinations of NIST standard 1643d were accurate for most certified elements to within 5% of the certified value (12% for Mo). Average results of 46 determinations of the Canadian NWRI standard TM23 gave values accurate to within 10% of certified values where determinands were above detection limits (except for Zn, 35%).

6.4.3 Verification of data and databasing

In a large survey such as this, there is plenty of scope for errors to creep in. Aside from the usual analytical problems, we had problems of samples presented without any location, samples with the wrong location, mis-numbered bottles, broken or leaky bottles, incorrectly typed site details, mismatch of *upazila* names and location, and incorrect and mismatching GIS coverages. Hopefully we have corrected or removed most of the errors but some may remain. We therefore caution against the over-interpretation of single values in the datasets. If the conclusion from a single data value is very important, the same or a similar well should be resampled and reanalysed to confirm its value. GIS coverage was obtained from the WARPO/EGIS database distributed on CD-ROM by EGIS. We have endeavoured to produce maps that are as accurate as possible but their accuracy cannot in all cases be guaranteed.

All the data were entered into the BGS (Wallingford) laboratory database which is maintained using the Microsoft Access database system as a front-end to an Oracle database server. The ICP-AES data were imported directly from the instrument after data processing and quality-control checks. Other data had to be entered manually. Aside from the usual QA checks, we have attempted to find aberrant values based on various consistency checks, where possible, by (i) comparing the results from two independ-

ent methods of analysis; (ii) calculating the charge balance where a complete set of major components was available; (iii) double checking apparent anomalies shown up by the mapping, and (iv) using geochemical experience to highlight possible inconsistencies. If inconsistencies were found, these were checked carefully but values were only removed from the dataset if there were good grounds for suspecting that a mistake had been made.

6.4.4 Presentation of data

The national hydrogeochemical data have been analysed using summary statistics, making various cross tabulations and cross plots, preparing maps and in a limited number of cases, undertaking detailed geostatistical analysis. The summary presented here focuses on the groundwater arsenic issue. We hope that the database will provide a source of data for a broad range of future investigations.

The statistical analyses were either made using a standard spreadsheet (Excel) or with the Genstat statistical package. One of the important features of the results is the well-to-well variation in water quality. This has been studied using classical statistical techniques (analysis of variance) and geostatistical techniques. Results of these studies are given in the Chapter 9.

The maps were prepared either with a standard GIS system (ArcView) or with a scientific plotting program (CoPlot). Most of the maps are also included in the accompanying *Hydrochemical atlas*. The atlas should be consulted for a wider range of maps.

A number of decisions had to be made when preparing these maps and these decisions can significantly affect the visual impact of the maps, e.g. the extent of data processing (interpolation and smoothing), choice of the number of class intervals and their values, size of map, symbols and colours used, the order of printing different colours and the display medium (e.g. VDU, paper, transparency).

In most of the following national maps, class intervals were chosen on the basis of rounded quartiles. The inset in these maps shows the actual percentage frequency of each of the indicated class intervals (the bar colours correspond with those of the map symbols).

6.5 SITE CHARACTERISTICS

6.5.1 Distribution of sampled wells

A total of 2039 sites were sampled in the 1998 Phase I survey and 1495 in the 1999 Phase II survey, giving 3534 sites overall. This amounts to a sample density of approximately one per 37 km^2 or an average site-to-site separation of about 6 km. The distribution of sample sites can be seen in Figure 6.1. The areas of low sample density are those where access is particularly difficult, for example the Sundarbans region in the south-west, the flooded *haor* regions in Sunamganj to the north-east and in the Atrai basin to the west.

The distribution of sample sites based on the six administrative divisions is given in Table 6.1 and the distribution based on districts is given in Table 6.2. Sixty one of the sixty four districts were sampled, the remaining districts being in the CHTs. On average, there were 58 sam-

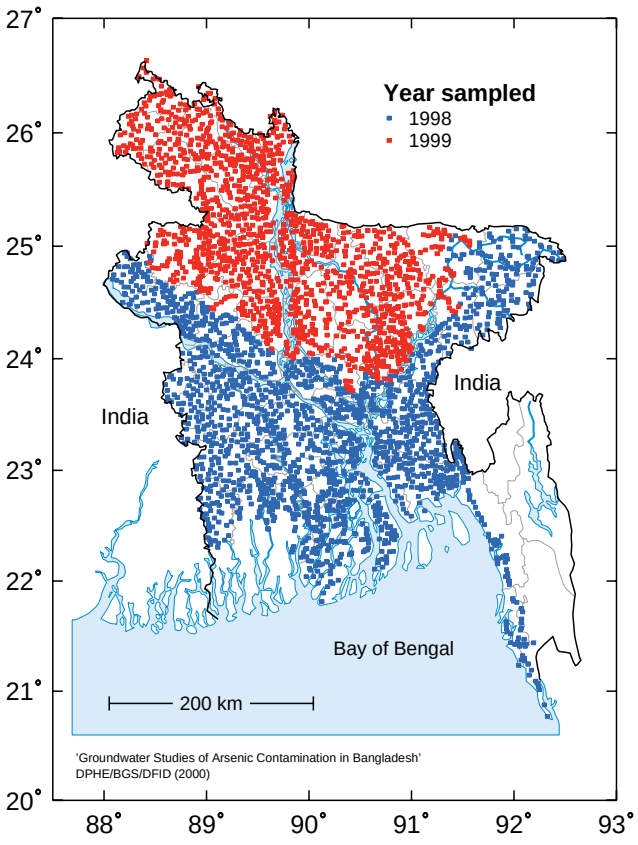

Figure 6.1. Distribution of well sites and year sampled for the DPHE/BGS National Hydrochemical Survey.

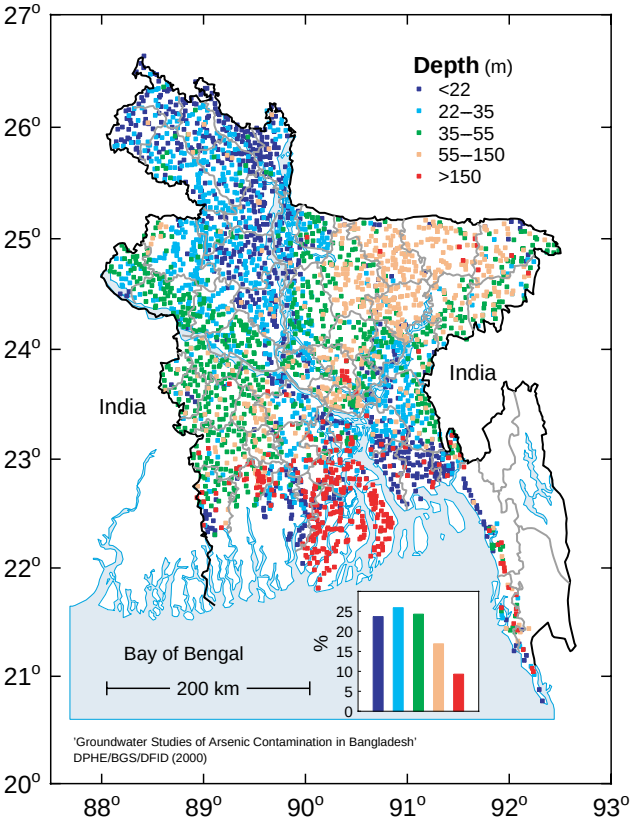

Figure 6.2. The depth distribution of wells sampled in the National Hydrochemical Survey.

Table 6.1. Number of districts visited and wells sampled in each division

Division	Number of districts visited	Number of wells sampled
Barisal	6	295
Chittagong	8	445
Dhaka	17	988
Khulna	10	474
Rajshahi	16	1072
Sylhet	4	260
All	61	3534

ples per district. Of the 496 *upazilas*, 433 were sampled, giving an average of about 8 samples per *upazila*.

6.5.2 Depth of sampled wells

The depth distribution of wells is shown in Figure 6.2 and classified in Table 6.3. Of the sampled wells, 69% were in the depth interval 15–60 m. As can be seen there is a distinct geographical distribution which is largely based on the minimum depth needed to obtain water of acceptable yield and quality (notably salinity). In the southern coastal region, mangrove swamps of the Sundarbans in the west mean that there are few people or wells present there. Further east, the wells either need to be very deep (greater than 150 m) as in the Barisal-Patuakhali region or very shallow, as in the Lakshmipur-Noakhali region further to the east, in order to avoid salinity. Relatively deep wells are also found in the Sunamganj-Sylhet region where shallow aquifers are poor or non-existent. Very shallow wells are also found in north-western Bangladesh where there is little or no overlying silt or clay layer. The cluster of deep wells in central Bangladesh corresponds with the deep wells of the city of Dhaka where extensive drawdown (and pollution) of the shallow aquifer necessitates the use of deep wells.

6.5.3 Age of sampled wells

The age distribution of wells is given in Tables 6.4 and 6.5. The tables illustrate 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. We could not find comparable statistics for other large-scale surveys and no national statistics for the age distribution of wells yet exist. Comparisons with such statistics as they become available will be an important test of the representativeness of our sampled 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.

6.6 ARSENIC

6.6.1 Overall statistics

A very large range in arsenic concentrations was found.

Table 6.2. Number of *upazilas* visited and wells sampled in each sampled district

District	Number of *upazilas* visited	Number of wells sampled
Bagerhat	9	62
Barguna	5	33
Barisal	10	92
Bhola	6	48
Bogra	11	94
Brahamanbaria	7	53
Chandpur	7	59
Chittagong	10	44
Chuadanga	4	34
Comilla	12	110
Cox's Bazar	6	43
Dhaka	6	45
Dinajpur	13	94
Faridpur	8	63
Feni	6	53
Gaibandha	7	71
Gazipur	5	44
Gopalganj	5	42
Habiganj	8	59
Jaipurhat	5	40
Jamalpur	7	63
Jessore	8	69
Jhalakati	4	33
Jhenaidah	6	54
Khulna	9	76
Kishoreganj	13	107
Kurigram	9	77
Kushtia	6	47
Lakshmipur	4	34
Lalmonirhat	5	39
Madaripur	4	36
Magura	4	32
Manikganj	7	47
Moulvibazar	6	53
Meherpur	2	15
Munshiganj	6	46
Mymensingh	12	108
Naogaon	11	92
Narail	3	24
Narayanganj	7	30
Narsingdi	6	56
Natore	6	51
Nawabganj	5	45
Netrokona	10	76
Nilphamari	6	53
Noakhali	5	49
Pabna	9	78
Panchagarh	5	39
Patuakhali	6	42
Pirojpur	7	47
Rajbari	4	34
Rajshahi	9	78
Rangpur	8	86
Satkhira	7	61
Shariatpur	6	49
Sherpur	5	51
Sirajganj	9	89
Sunamganj	10	71
Sylhet	11	77
Tangail	11	91
Thakurgaon	5	46

Table 6.3. Percentage of wells in each division classified by well depth and division

	Well depth interval (m							
Division	**<15**	**15–30**	**30–60**	**60–90**	**90–150**	**150–200**	**>200**	**All**
Barisal	7	23	3	0	1	1	66	100
Chittagong	18	39	27	3	4	2	7	100
Dhaka	4	26	41	21	4	1	3	100
Khulna	4	15	59	7	6	2	7	100
Rajshahi	11	55	31	1	1	0	0	100
Sylhet	2	7	42	19	26	3	<1	100
All	8	33	36	9	5	1	8	100

Table 6.4. The number of wells sampled, classified by age and division

	Year well constructed								
Division	**Not known**	**before 1970**	**1970–74**	**1975–79**	**1980–84**	**1985–89**	**1990–94**	**1995 or later**	**All**
Barisal	2	10	10	8	26	26	100	113	295
Chittagong	1	9	19	21	37	63	134	161	445
Dhaka	19	18	23	59	82	116	253	418	988
Khulna	4	10	15	45	55	74	112	159	474
Rajshahi	13	5	13	64	63	115	295	504	1072
Sylhet	3	6	8	14	22	44	64	99	260
All	42	58	88	211	285	438	958	1454	3534

Table 6.5. The percentage of wells sampled, classified by age and division

	Year well constructed								
Division	**Not known**	**before 1970**	**1970–74**	**1975–79**	**1980–84**	**1985–89**	**1990–94**	**1995 or later**	**All**
Barisal	1	3	3	3	9	9	34	38	100
Chittagong	0	2	4	5	8	14	30	36	100
Dhaka	2	2	2	6	8	12	26	42	100
Khulna	1	2	3	9	12	16	24	34	100
Rajshahi	1	0	1	6	6	11	28	47	100
Sylhet	1	2	3	5	8	17	25	38	100
All	1	2	2	6	8	12	27	41	100

The minimum concentration found was less than 0.25 μg L^{-1} and the maximum found was 1670 μg L^{-1}, a range of four orders of magnitude. Only two samples (0.06% of all samples) exceeded 1000 μg L^{-1}. 850 samples (24% or one quarter of all samples) fell below the instrumental detection limit which was normally 0.25 or 0.5 μg L^{-1}. It is likely that the lowest concentrations were actually a few ng L^{-1} or lower. It is therefore quite possible that the true range could be as large as six orders of magnitude or more when the low concentrations in the Dupi Tila aquifer are eventually quantified.

The large proportion of 'less than' values complicates the calculation of many statistical parameters, e.g. means and variances. No attempt was made to deal with this using the various statistically-based substitution methods that are available. Rather we have chosen to use non-parametric methods wherever possible and where a value was required, we have used half the detection limit as the substituted value.

Tables 6.6 and 6.7 summarise the results in terms of percentiles. The median concentration was 4.0 μg L^{-1}. 42% of all samples exceeded 10 μg L^{-1} (the WHO guideline value for drinking water) and 25% (one quarter) exceeded 50 μg L^{-1} (the Bangladesh standard). If only shallow wells (<150 m) are considered, the percentages increase to 46% and 27%, respectively. 9% of samples exceeded 200 μg L^{-1}. The maximum reported groundwater As concentration in Bangladesh is about 4 mg L^{-1} from Chatkhil, Noakhali district in SE Bangladesh.

Clearly the groundwater arsenic problem is very serious in terms of both the number of exceedances and the scale of the exceedances. The average concentration was approximately 55 μg L^{-1}. Average concentrations are related to the average dose of arsenic taken in with drinking water and are therefore important from the health point of view.

Below, we examine the distribution of arsenic as a function of various features such as well location and well depth and age. Care should be taken in interpreting these data both in terms of the statistics derived (we cannot guarantee that a truly random distribution of wells was sampled) and even qualitatively in terms of the trends observed. The concentration of arsenic in groundwater depends on many factors, not all of which are adequately

Table 6.6. Distribution of arsenic concentrations in the complete dataset expressed as percentiles (n=3534)

Percentile	Arsenic concentration (µg L^{-1})
10	<1
20	<1
30	<1
40	1.6
50	4.0
60	13
70	31
80	73
90	181
95	302
99	558
99.9	891

Table 6.7. Percentage of samples below or exceeding various concentration thresholds (n=3534)

Arsenic concentration (µg L^{-1})	Percentage of samples exceeding threshold concentration	Percentage of samples below threshold concentration
5	48	52
10	42	58
20	35	65
30	31	69
40	27	73
50	25	75
100	16	84
200	9	91
300	5.1	94.9
500	1.79	98.21
1000	0.06	99.94

represented in our database. Statistically significant correlations may therefore result from the operation of other unseen but correlated variables.

It may be significant that the two sampling campaigns for our national survey were carried both out at the end of the dry season and so, if as some initial observations indicate, As concentrations are measurably greater during the wet season than during the dry season, then our regional survey of As must be viewed as being somewhat conservative, i.e. if anything, low.

6.6.2 Geographical distribution of arsenic

There is a distinct geographical distribution of arsenic with the greatest concentrations in the south and south-east and the smallest concentrations in the north and north-west of Bangladesh. This can be seen in a map of the point-source data (Figure 6.3) but the regional trends are more clearly seen in the smoothed map (Figure 6.4). In the arsenic point source map, and other similar maps shown in this Chapter, the lowest concentration class symbols have been plotted first, then the symbols for the next lowest class, and so on. Therefore where there is some overlap of symbols, the higher concentration symbol will fall on top of the lower symbol and will tend to dominate the map.

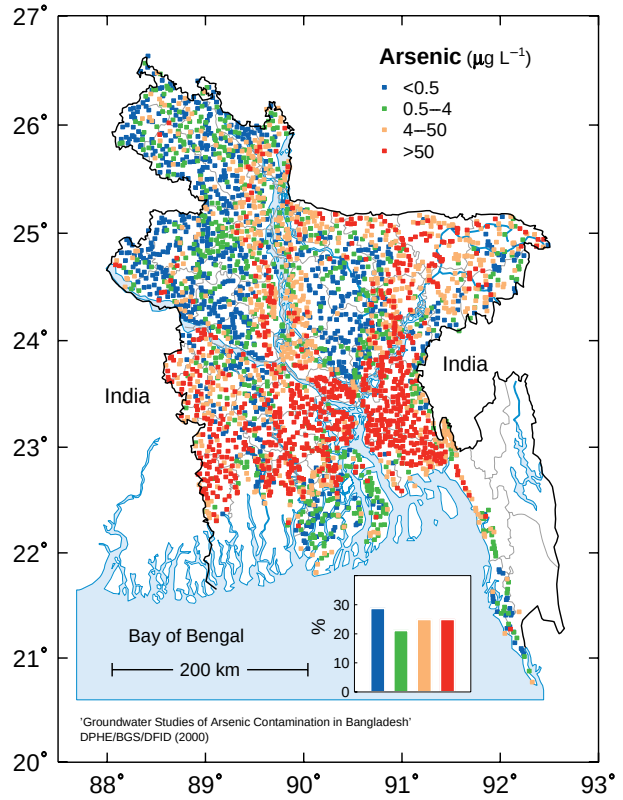

Figure 6.3. Map of point-source arsenic concentrations observed in groundwaters in the National Hydrochemical Survey. Inset shows the percentage frequency of each of the indicated class intervals (bar colours match those of the map symbols).

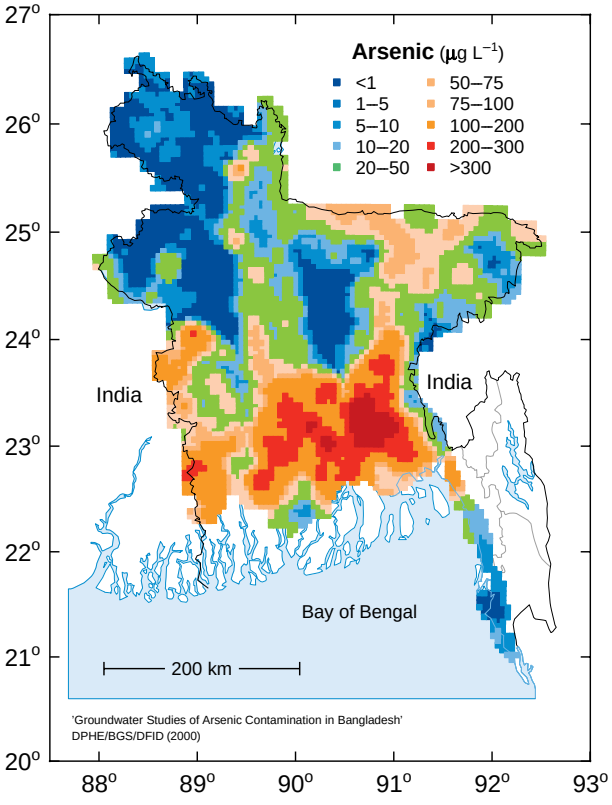

Figure 6.4. Map of smoothed groundwater arsenic concentrations from the National Hydrochemical Survey. Smoothing was carried out by disjunctive kriging.

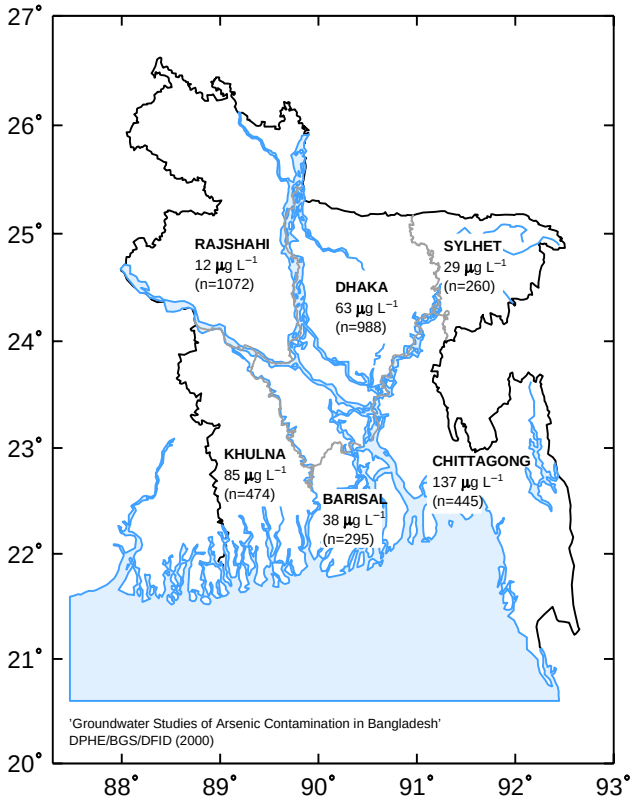

Figure 6.5. Average concentration of arsenic in wells from each of the six administrative divisions. Note that the Chittagong division includes the area east of Dhaka as well as the narrow strip of land sampled along the SE coast of Bangladesh. No wells were sampled in the Chittagong Hill Tracts.

There is a large variation in the average arsenic concentration found in each administrative division (Figure 6.5). This varies from 12 µg L^{-1} in Rajshahi Division to 137 µg L^{-1} in Chittagong Division (which includes the highly contaminated district of Chandpur). All divisions contain at least one well which exceeds the Bangladesh standard, as do 53 of the 61 districts (Table 6.8). 249 or 58% of the 433 sampled *upazilas* contained at least one well exceeding the Bangladesh standard.

The most contaminated district was found to be Chandpur with 90% of the sampled wells exceeding the Bangladesh standard and with an average arsenic concentration of 366 µg L^{-1} (Table 6.9). The remaining 11 most-contaminated districts had 60% or more of their sampled wells above the Bangladesh standard and average As concentrations exceeding 100 µg L^{-1}. In most districts, there were at least some wells with As concentrations less than 10 µg L^{-1} especially in the occasional deep well. A broad north-south band of low As wells is found in SE Bangladesh. This follows the Gorai-Bhairab valleys and may reflect a palaeochannel (Chapter 3).

The most-contaminated districts contrast sharply with the least-contaminated districts (Table 6.10). Only one district, Thakurgaon in the extreme north-west of Bangladesh, had no sampled wells exceeding the WHO guideline value. Eight districts had no sampled wells exceeding the Bangladesh standard. These were either southern coastal districts which are dominated by deep wells or north-western districts where contamination is regionally lower. Perhaps more significant is the contrast in average arsenic concentration which exceeds 100 µg L^{-1} in the most-contaminated districts to just a few µg L^{-1} in the least-contaminated districts.

Table 6.8. Number of administrative areas with at least one sampled well exceeding a drinking-water standard

	Number of administrative areas				
	Bangladesh standard (50 µg L^{-1})		WHO guideline value (10 µg L^{-1})		
	Below	Above	Below	Above	Total
Divisions	0	6	1	5	6
Districts	8	53	1	60	61
Upazilas	184	249	39	394	433

This emphasises the need to identify the worst-contaminated regions for priority action. However, there are some seriously contaminated wells even in the least-contaminated districts (Table 6.10) and so the mitigation strategy must also find these wells. The town of Chapai Nawabganj is one such 'hot spot' which appears to be about 5 × 3 km in size. The sample density of our national survey was insufficient to ensure that all hot spots were detected and indeed the Chapai Nawabganj hot spot was only identified by more detailed sampling. A number of other hot spots have been detected in northern Bangladesh by patient identification and field testing. While such hot spots undoubtedly present a serious situation, they are atypical and should not disproportionately detract the mitigation programme from the more extensive contamination in southern and south-eastern parts of the country.

6.6.3 Arsenic concentration versus well depth

Perhaps the most important distinction in arsenic concentrations is between shallow and deep wells (Figure 6.6). The situation is even clearer if the results are cross-tabulated (Table 6.11). Wells deeper than 150 m–200 m show a sharp reduction in their average arsenic concentration and in the percentage of wells that exceed both the WHO guideline value and the Bangladesh standard (Table 6.12). The 'cut-off' depth depends on geographic location. Even though only 4% of sampled wells in the 100–150 m depth range, 37% of them exceeded 50 µg L^{-1}. Therefore, in many areas it appears that it would not be sufficient to drill just a little deeper for low-As water but wells would need to exceed at least 150 m to provide low-As water.

It is interesting to note that there appears to be a 'bell-shaped' depth profile for the average As concentration, with the maximum average contamination being found in the 15–30 m interval. This trend is upset by the relatively large percentage of wells in the 90–150 m interval that are contaminated but this probably reflects the peculiar aquifer conditions in the Sylhet region from where most of these samples were derived. A broadly similar bell-shaped depth trend has long been known in West Bengal where the aquifer has traditionally been divided into three units with the middle unit, Unit 2, being described as the 'arseniferous' unit (PHED, 1991; Bhattacharya et al.,

Table 6.9. Arsenic statistics for the twelve most contaminated districts

District	Number of wells sampled	Average As concentration (μg L^{-1})	Minimum As concentration deep/ shallow (μg L^{-1})	%age of wells in given As concentration class (μg L^{-1})				%age of wells exceeding 50 μg L^{-1}
				<10	10–50	50–200	>200	
Chandpur	59	366	2/51	8	2	10	80	90
Madaripur	36	191	1/<1	31	0	31	39	69
Munshiganj	46	189	3/2	9	9	41	41	83
Gopalganj	42	187	21/<1	17	5	43	36	79
Lakshmipur	34	179	2/<1	24	21	26	29	56
Noakhali	49	162	4/2	16	14	37	33	69
Bagerhat	62	156	<1/<1	19	21	31	29	60
Shariatpur	49	151	2/<1	24	10	35	31	65
Comilla	110	142	<1/<1	29	5	37	28	65
Faridpur	63	140	<1/5	24	11	35	30	65
Satkhira	61	133	2/<1	18	15	41	26	67
Meherpur	15	116	<1/-	7	33	40	20	60

Table 6.10. Arsenic statistics for the twelve least-contaminated districts

District	Number of wells sampled	Average As concentration (μg L^{-1})	Maximum As concentration (μg L^{-1})	%age of wells in given As concentration class (μg L^{-1})				%age of wells exceeding 50 μg L^{-1}
				<10	10–50	50–200	>200	
Thakurgaon	46	1	6	100	0	0	0	0
Natore	51	1	18	96	4	0	0	0
Barguna	33	1	11	97	3	0	0	0
Jaipurhat	40	1	13	98	3	0	0	0
Lalmonirhat	39	1	16	97	3	0	0	0
Nilphamari	53	2	23	94	6	0	0	0
Panchagarh	39	3	34	95	5	0	0	0
Patuakhali	42	3	17	93	7	0	0	0
Dinajpur	94	3	54	95	3	2	0	2
Cox's Bazar	43	3	70	95	2	2	0	2
Gazipur	44	4	155	98	0	2	0	2
Naogaon	92	6	244	95	3	1	1	2

Table 6.11. Two-way classification of tubewells according to their arsenic concentration and depth

	%age of wells in a given depth range that are in a given arsenic concentration range							
	As concentration range (μg L^{-1})							
Depth range (m)	<10	10–50	50–100	100–150	150–200	200–300	>300	Total%
<25	53	17	9	5	3	4	8	100
25-50	57	16	9	4	3	5	6	100
50-100	55	22	10	5	3	3	2	100
100-150	26	37	27	5	2	3	0	100
150-200	78	19	3	0	0	0	0	100
>200	97	2	0	0	0	0	0	100

1997). Chowdhury et al. (1999) have also noted a very similar distribution of contaminated wells in West Bengal to that observed here.

It is important to appreciate the geographical spread of shallow and deep wells in our surveys since, as discussed above, this is far from uniform (Table 6.3). Broadly, many of the sampled wells in the 150–200 m depth interval are from the Sylhet region, while those with depths greater than 200 m are mostly from the southern coastal region. Very few deep wells were found or sampled in the rest of Bangladesh. Therefore, it is not possible to extrapolate the results from the relatively few deep wells sampled here to those other parts of Bangladesh that are not well represented by the current samples.

Of the few deep groundwaters investigated in Faridpur as part of our investigations in the Special Study Areas, a few exceedances above 10 μg L^{-1} were noted (Chapter 7). In addition, some relatively high concentrations have been

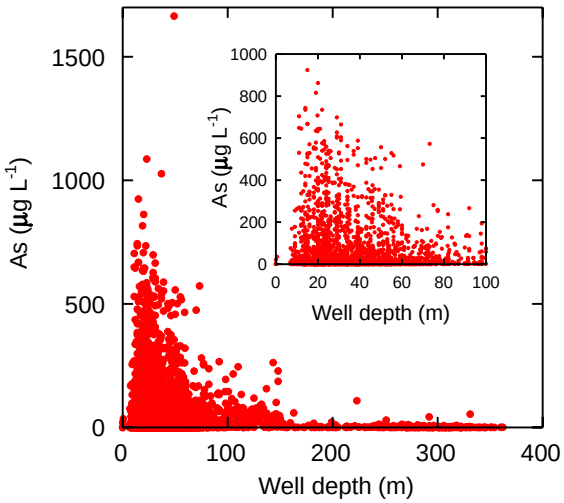

Figure 6.6. Concentration of arsenic plotted against well depth for all sampled wells.

Table 6.12. Average concentration of arsenic in wells as a function of well depth

Depth interval (m)	Number of wells	% of wells	Average As concentration (µg L^{-1})	% of wells with >50 µg L^{-1}
<15	287	8	58	25
15–30	1180	33	76	31
30–60	1258	36	56	26
60–90	317	9	33	21
90–150	165	5	45	35
150–200	32	1	7	1
>200	295	8	3	1
All	3534	100	55	25

found in groundwaters from 'deep' tubewells recently installed by DPHE with UNICEF assistance throughout the As-affected areas of Bangladesh. Of 170 'deep' tubewells drilled to assess the presence of, and water quality in, the deep aquifer, 95% were below the Bangladesh arsenic standard. The exceptions were wells at 700 ft in Faridpur which contain As just above the standard. Additional wells are being installed nearby to test whether this a problem of well construction or reflects contamination of the deep aquifer. The issue of the development of the deep aquifer is discussed in more detail in the Chapter 13.

6.6.4 Arsenic versus geology

Each of the sampled wells was assigned to a geological unit based on the Geological Survey of Bangladesh classification as given by the most recent geological map of Bangladesh (Alam et al. 1990). This allocation was based on the GPS measured well position and a digital form of the geological map given in the WARPO/EGIS database. This procedure is susceptible to errors and approximations arising from errors in the GPS location, the geological map and the arsenic database. Therefore not too much weight should be given to the classifications of individual sites. Nevertheless, the overall trends are interesting and of greater reliability. It should also be remembered that this geological classification is only based on the surface geology, and in that respect can only be expected to have a direct influence on the behaviour of the underlying aquifer where there is a close relationship between surface geology and subsurface geology. As the depth of the well increases, this relationship is likely to become weaker.

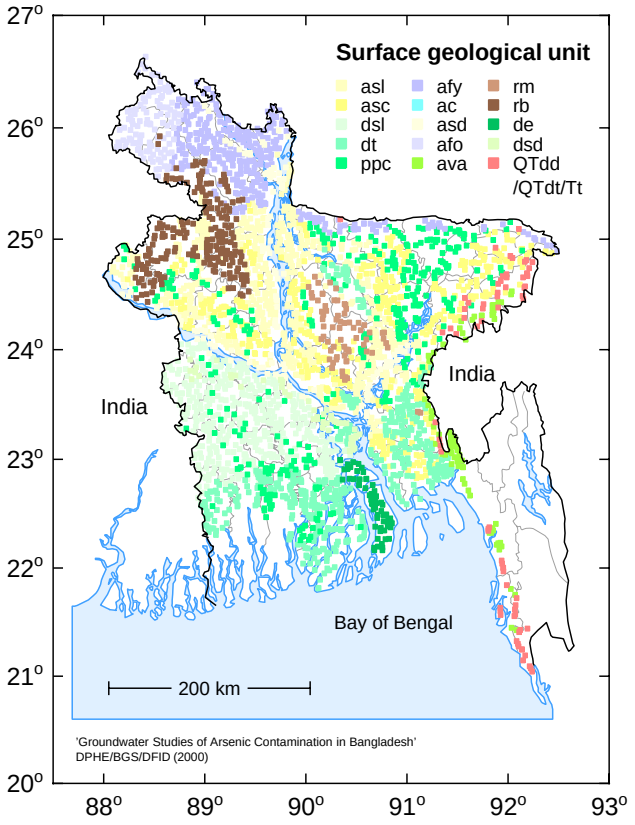

Figure 6.7. Classification of survey sample sites by geological unit. See Table 6.12 for details of the GSB abbreviations used in the legend.

The classification of sites by surface geological unit (Figure 6.7) and by average arsenic concentration within each unit (Table 6.13) shows that the highest arsenic concentrations are found in the recent deltaic and alluvial deposits. These are also the most abundant deposits. The lowest concentrations are consistently found beneath the older Tertiary and Quaternary deposits including the Barind and Madhupur Clay. Interestingly, the 'old gravelly sand' unit, and to a lesser extent the 'young gravelly sand' unit, have low concentrations. These form part of the Tista Fan in north-western Bangladesh. The highest average concentrations are found beneath the Chandina alluvium and Deltaic silt and sand. As always, care must be taken when interpreting such differences since arsenic concentrations in groundwater reflect many factors of which surface geology is just one. The most significant observation is that high arsenic concentrations are confined to recent (Holocene) sediments – conversely, the older sediments

Table 6.13. Classification of sample sites (n=3534) and average arsenic concentrations based on the estimated geological unit (sorted by decreasing average arsenic concentration)

Geological unit	GSB code	No. of wells	% of wells in unit	Average As (µg L^{-1})
Chandina alluvium	ac	183	5.2	162
Deltaic silt	dsl	428	12.1	105
Deltaic sand	dsd	57	1.6	99
Alluvial sand	asd	117	3.3	67
Tidal deltaic deposits	dt	352	10.0	64
Alluvial silt and clay	asc	476	13.5	61
Marsh clay and peat	ppc	345	9.8	52
Alluvial silt	asl	599	17.0	43
Estuarine deposits	de	68	1.9	38
Valley alluvium & colluvium	ava	83	2.3	23
Beach and dune sand	csd	22	0.6	20
Young gravelly sand	afy	326	9.2	17
Barail Formation	Tba	1	<0.1	14
Dupi Tila Formation	QTdt	14	0.4	6
Dihing & Dupi Tila undiv.	QTdd	42	1.2	6
Tidal mud	dm	2	0.1	4
Old gravelly sand	afo	111	3.1	2
Boka Bil Formation	Tbb	5	0.1	2
Tipam Sandstone Formation	Tt	19	0.5	2
Girujan clay	QTg	4	0.1	1
Barind clay residuum	rb	205	5.8	<1
Madhupur clay residuum	rm	73	2.1	<1
Mangrove swamp	dsw	1	<0.1	<1
Dihing Formation	Qtdi	1	<0.1	<1

are essentially arsenic-free.

6.6.5 Arsenic versus year of construction of sampled wells

The data for the shallow wells (<150 m deep) were divided into six 'arsenic' classes (<10, 10–50, 50–100, 100–200, 200–300 and >300 µg L^{-1}) and seven 'Year constructed' classes (before 1970, 1970–74, 1975–79, 1980–84, 1985–89, 1990–1994 and since 1995). Deep wells were excluded because most of the arsenic concentrations were very low, frequently below the detection limit, and it is reasonable to expect that any relationship between arsenic concentration and age of well would vary with well depth. The number of sampled wells in each class is shown in Table 6.14. The large number of wells that exceed the Bangladesh standard and which were constructed since 1990 is striking. This reflects the large number of wells constructed in recent years, even after awareness of the arsenic problems in Bangladesh was raised.

It is more revealing to express the numbers in terms of percentages (Table 6.15). There is a distinct trend for the older wells to be more contaminated than the younger wells. It is tempting to deduce from this that the shallow wells become more contaminated with time. This may be true but these data do not by themselves prove this to be the case. There could be other correlated variables that may account for the trend. For example, we have already demonstrated (Table 6.5) that proportionately more wells have been drilled recently in the Rajshahi Division and this is a generally low-arsenic area. The only sure way of dem-

Table 6.14. Number of shallow wells (less than 150 m deep) in given arsenic and 'Year constructed' classes and exceeding water-quality standards

	Number of wells in arsenic concentration (µg L^{-1}) class							Bangladesh standard	WHO guideline value
Year constructed	<10	10–50	50–100	100–200	200–300	>300	All	n>50 µg L^{-1}	n>10 µg L^{-1}
Before 1970	12	9	10	10	2	5	48	27	36
1970–75	25	19	14	8	7	10	83	39	58
1975–80	87	42	26	17	20	13	205	76	118
1980–85	130	54	37	21	13	13	268	84	138
1985–90	200	78	42	33	22	33	408	130	208
1990–95	464	153	76	78	36	59	866	249	402
Since 1995	797	230	108	79	36	46	1296	269	499
All years	1715	585	313	246	136	179	3174	874	1459

Table 6.15. Percentage of shallow wells in given arsenic and 'Year constructed' classes

	% of total wells in arsenic concentration (µg L^{-1})class							Bangladesh standard	WHO guideline value
Year constructed	<10	10–50	50–100	100–200	200–300	>300	All	%>50 µg L^{-1}	%>10 µg L^{-1}
Before 1970	25	19	21	21	4	10	100	0.9	1.1
1970–74	30	23	17	10	8	12	100	1.2	1.8
1975–79	42	20	13	8	10	6	100	2.4	3.7
1980–84	49	20	14	8	5	5	100	2.6	4.3
1985–89	49	19	10	8	5	8	100	4.1	6.6
1990–94	54	18	9	9	4	7	100	7.8	12.7
Since 1995	61	18	8	6	3	4	100	8.5	15.7
All years	54	18	10	8	4	6	100	27.5	46.0

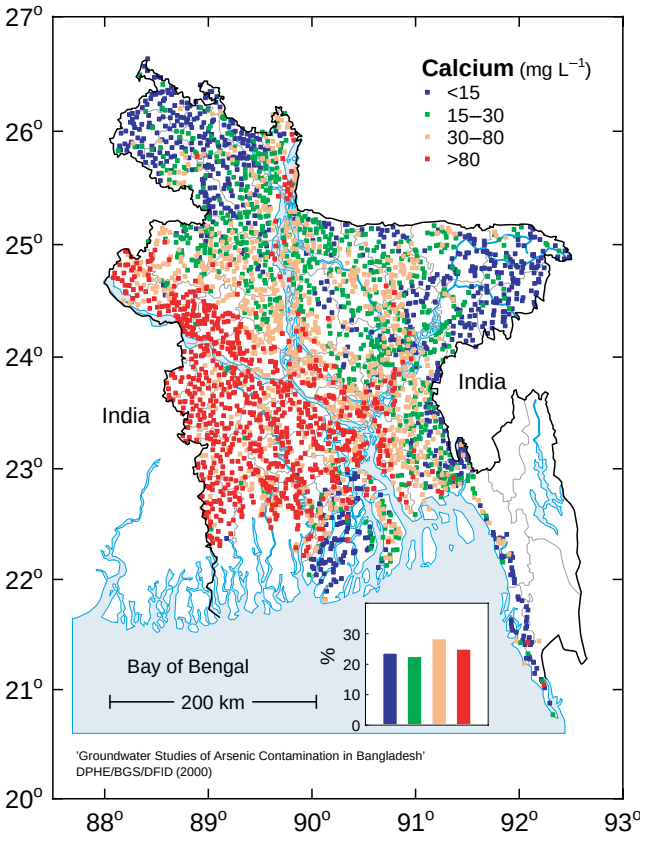

Figure 6.8. Spatial distribution in calcium from the National Hydrochemical Survey.

onstrating changes with time is to monitor these changes in a systematic way. This makes it difficult to quantify changes that take place over more than a few years. As better models for the evolution of the arsenic-rich groundwaters are developed, then a better insight into possible long-term changes should emerge.

6.7 Magnesium, calcium, strontium and barium

The groundwater chemistry can sometimes give clues indirectly to the probable composition of aquifer sediments without the benefit of a sediment analysis. This is particularly true for the alkaline earth elements since their concentrations in groundwater are often controlled by carbonate minerals which usually equilibrate rapidly with groundwater. The absence of pH and bicarbonate data from the National Hydrochemical Survey dataset means that saturation indices for these minerals cannot be calculated but data from the Special Study Areas where these data are available suggests that there is both calcite and dolomite saturation (even slight supersaturation) in the samples from all three areas.

The regional distribution of Ca in the Bangladesh groundwaters is shown in Figure 6.8 and maps for Mg, Sr and Ba are given in the *Hydrochemical atlas*. It is clear from the maps that the three alkaline earth cations, Mg^{2+}, Ca^{2+} and Sr^{2+}, are quite variable in concentration, yet the maps show similar spatial patterns. They also show the highest inter-element correlations (after log-transforming the data). Barium is also correlated with this group but less strongly so. This correlation probably reflects the distribution of free carbonates in the original sediments with the high concentrations of Ca in the groundwater reflecting their presence and relatively low concentrations reflecting their absence. The most probable carbonate minerals are calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). Mg^{2+} and Sr^{2+} readily substitute for Ca^{2+} in calcite but Ba^{2+} does so much less readily because of its substantially larger ionic radius. It must be remembered that such inferences are likely to reflect most strongly the aquifer sediments from where the water has been pumped (i.e. older sediments at depth rather than recently-deposited surface sediments) and that in very old sediments, there is the possibility that some of the original, more soluble minerals may have been completely flushed away.

It appears from the maps that the Holocene sediments derived from the River Ganges (south-western and south-central Bangladesh) probably contain free calcium-magnesium carbonates. Soils developed on the sediments in this region are also defined as carbonate-rich (Brammer, 1996). In contrast, the Holocene sediments of the Tista Fan (north-west) and the north-east *haor* region, as well as the older Quaternary and Tertiary sediments of the Chittagong area probably do not. Concentrations of Ca in these latter groundwaters are less than 15 mg L^{-1}. This is also true for the deep groundwaters from the southern coastal region. In western and central Bangladesh, the distinctive boundary of the high-Ca groundwaters corresponds with the limit of the Holocene sediments of the Atrai Floodplain.

These alkaline earth elements are also derived from other minerals which reduces the overall correlations. Where there has been a substantial inundation of old seawater, some Mg may remain from this source: for every 8.3 mg L^{-1} of Na derived from seawater, there will be about 1 mg L^{-1} Mg and negligible amounts of Ca (0.3 mg L^{-1}), Sr (6 µg L^{-1}) and Ba (2 µg L^{-1}). The effects of ion exchange will cloud this simple relationship to some extent.

6.8 Iron and manganese

Maps of the distributions of Fe and Mn are given in Figures 6.9 and 6.10. Concentrations of iron and manganese are high in most of the groundwaters of Bangladesh as a result of the predominance of reducing conditions in the aquifers. The distribution of Fe shows some relationship with As, although the overall correlation is weak in some areas. Despite the fact that both Fe and Mn are redox-controlled, the spatial patterns of each differ and indicate the differing behaviour of the two elements as the sediments and groundwaters undergo reduction.

Iron is released by reductive dissolution of iron oxides and weathering of mafic minerals (e.g. biotite). Manganese is released by reductive dissolution of manganese oxides. The differences between iron and manganese distributions are related to their different positions in the redox sequence – as the redox potential is lowered (environment becomes reducing), Mn(IV) will tend to be reduced before Fe(III) but after the dissolved oxygen and nitrate have been consumed. At the near-neutral pH values of most Bangladesh groundwaters, Mn(II) is also much more

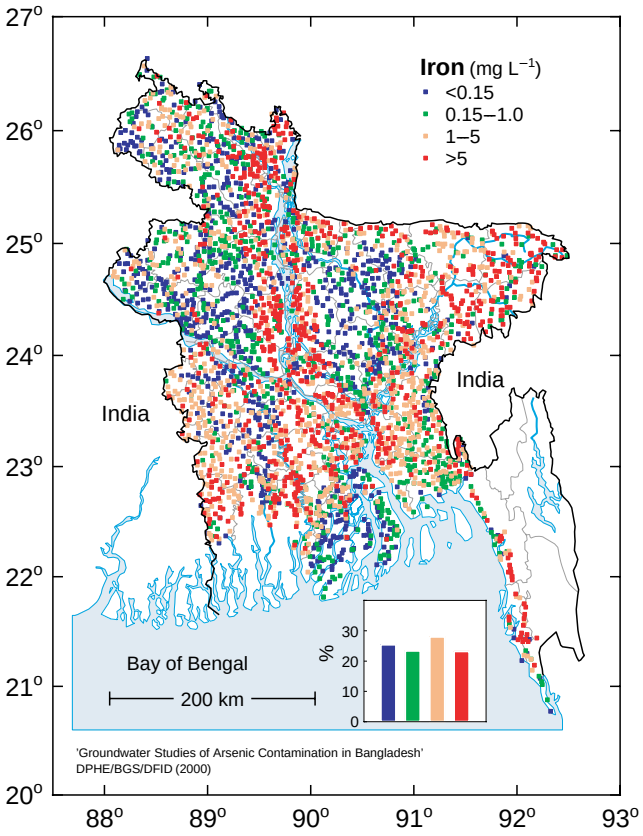

Figure 6.9. Spatial variation of iron in groundwaters from the National Hydrochemical Survey.

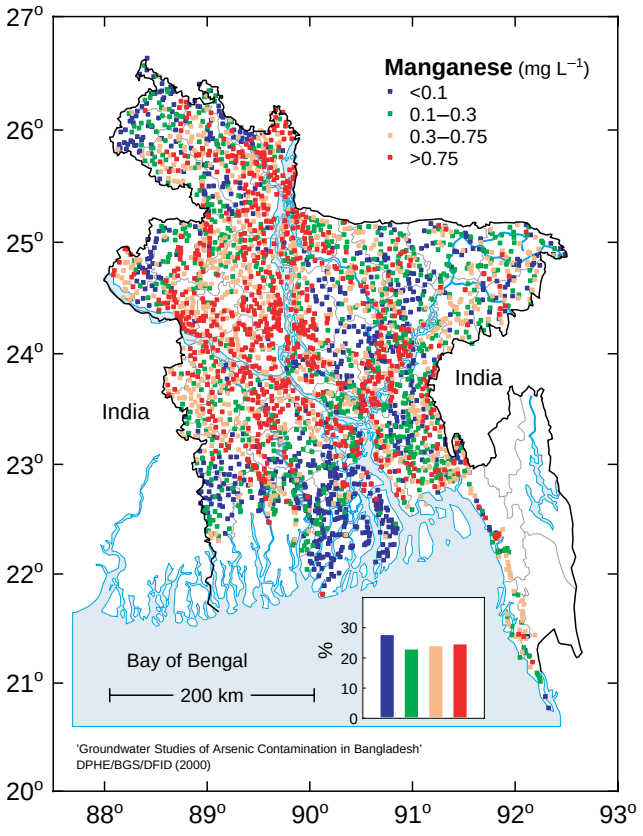

Figure 6.10. Spatial variation of manganese in groundwaters from the National Hydrochemical Survey.

slowly oxidised and precipitated than Fe(II). Highest manganese concentrations may therefore be expected to exist in groundwaters which are less strongly reducing than those with high arsenic concentrations.

The median Fe concentration observed was 1.1 mg L^{-1} and the maximum was 61 mg L^{-1}. Concentrations of Fe are high but patchy in southern Bangladesh (south of the River Ganges) and in the north-east (Sylhet Basin). The proportion of wells with high iron concentrations and the absolute concentrations are particularly high in the Jamuna Valley, with many wells exceeding 10 mg L^{-1} Fe. The median concentration of Fe in As-contaminated (>50 μg L^{-1}) shallow groundwaters is 4 mg L^{-1}.

Lowest overall Fe concentrations are found in the groundwaters from the Barind and Madhupur Tracts, the deep groundwaters of Barisal region and in north-western parts of the Tista Fan. 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 oxides in these sediments may therefore be less labile (more oxidised, more crystalline) than that associated with the younger Holocene deposits. A band of relatively low-iron waters also follows the Gorai-Bhairab feature observed in the arsenic map.

In the Tista Fan, the low Fe concentrations probably relate to the occurrence of relatively oxidising conditions (and the presence of oxidised sands in the aquifers), coarse sediment grain size, low iron oxide content and relatively active groundwater movement. Iron-oxide coatings around sand grains have been recognised in sediments from the Tista Fan (Thakurgaon district, Imam et al., 1998).

This highlights the large difference of Fe concentrations between the shallow and deep aquifers, a distinction also 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 higher concentrations are believed to reflect the distribution of groundwaters which are less reducing than those found in the lower parts of the Bengal delta.

Maps have also been prepared of the distribution of manganese concentrations based on health-related class boundaries *(*see the *Hydrochemical atlas*) and also for the relationship between manganese and arsenic (Figure 6.11). The Bangladesh standard for Mn on both health and aesthetic grounds is 0.1 mg L^{-1}. 74% of groundwater samples collected in the survey exceeded this value and 35% exceeded the WHO guideline value of 0.5 mg L^{-1}.

Arsenic and manganese are the two elements for which the water quality standards are most commonly exceeded in Bangladesh. Some waters exceed one of these standards while others pass that standard yet fail the other standard. The correlation is important for assessing the overall distribution of risk. The joint arsenic and manganese map highlights the poor spatial correlation between the two elements. Many groundwaters from north-western Bangladesh in particular have low arsenic but high manganese

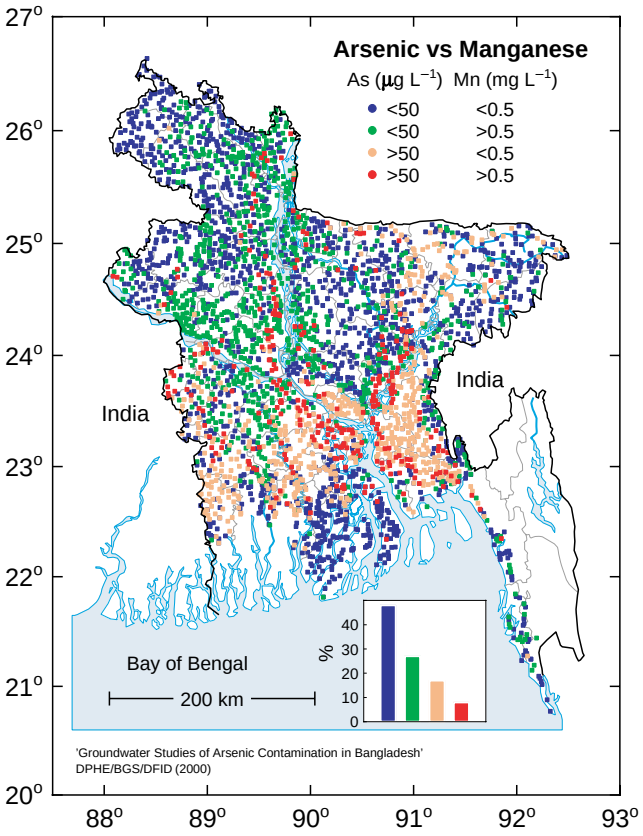

Figure 6.11. Combination distribution of arsenic and manganese in groundwaters from the National Hydrochemical Survey.

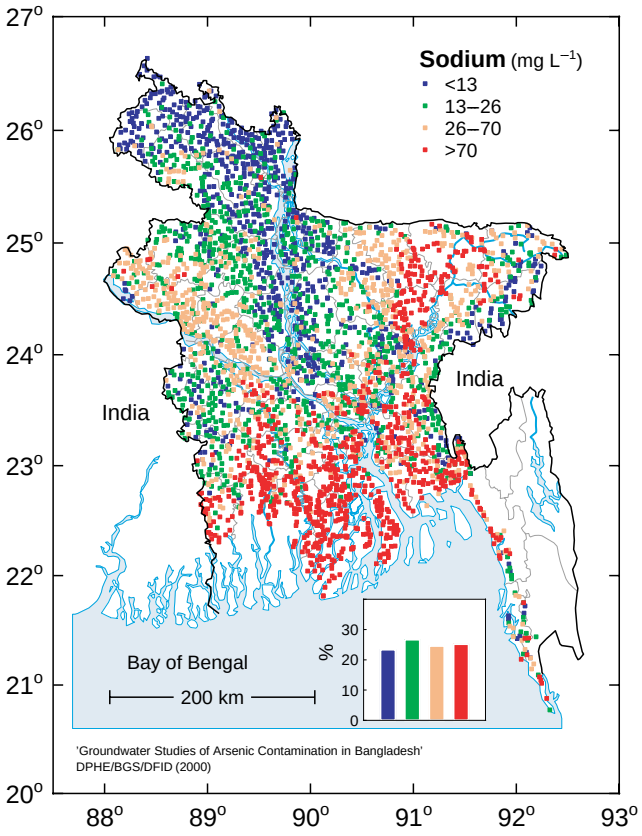

Figure 6.12. Spatial variation of sodium in groundwaters from the National Hydrochemical Survey.

concentrations. The survey showed that 8% of samples exceeded both 50 µg As L^{-1} and 0.5 mg Mn L^{-1}, while only 48% of samples were below both these criteria.

In other words, while approximately 25% of all sampled wells failed acceptability for drinking water because of their high arsenic concentrations (i.e. they exceed the Bangladesh standard), a further 55% will fail because they exceed the Bangladesh manganese standard. 27% of the samples which had arsenic concentrations below 50 µg L^{-1} had manganese concentrations above 0.1 mg L^{-1}. 62% of samples failed one or other of the two WHO guideline values. Groundwater from the Barind and Madhupur Tracts, the deep aquifer in the southern coastal region of Bangladesh and Sylhet (and Dhaka) and from the coarser sediments of north-western Bangladesh tended to comply on both counts.

There is a significant difference between the scale of exceedances in shallow and deep wells. 39% of shallow wells exceeded the WHO guideline value for Mn and 67% exceeded one or other of the As and Mn WHO guideline values. 86% exceeded one or other of the Bangladesh standards. Corresponding figures for deep wells were 7% and 23%, respectively. Therefore most deep wells comply with the WHO guideline values for both As and Mn.

6.9 Sodium, potassium and boron

These elements are indicators of groundwater salinity and reflect relict seawater influences either by marine inundation of low-lying areas or saline intrusion of near-coastal aquifers. Potassium in particular also has an important relationship with mineral reactions (weathering of clays, ion exchange) and so although the distribution of K concentrations has some relationship to those with Na and B, some notable differences also occur (Figures 6.12, 6.13 and 6.14.

Concentrations of Na, K and B are in general greater in the deep groundwaters sampled in the National Hydrochemical Survey, although this is because a large proportion of these were collected from the Barisal region of southern (coastal) Bangladesh, as well as from the Sylhet region. Electrical conductivity logs of deep boreholes from the southern coastal region show a great deal of variability of salinity with depth. Very fresh water can often be found at considerable depth in the region (e.g. usually at depths greater than 250 m), as found in the 275 m tubewell in the DPHE compound at the Lakshmipur piezometer monitoring site (Chapter 10). However, in practice, somewhat shallower (but still 'deep') and slightly more saline aquifers are commonly exploited.

Figures 6.12, 6.13 and 6.14 show that the highest concentrations of Na, K and B are mainly found in the south and south-eastern parts of Bangladesh and in the low-lying haor region of the north-east. Occasional, locally high Na and B (though not K) concentrations are also found in the Atrai basin in western Bangladesh just north of the Ganges floodplain. Following the last glacial period, rising sea levels resulted in marine inundation of these areas between around 6500–4000 years ago (Chapter 3). 5.3% of samples exceeded the WHO guideline value for B (0.5 mg L^{-1}) and 9.1% exceeded the former guideline value of 0.3 mg L^{-1}.

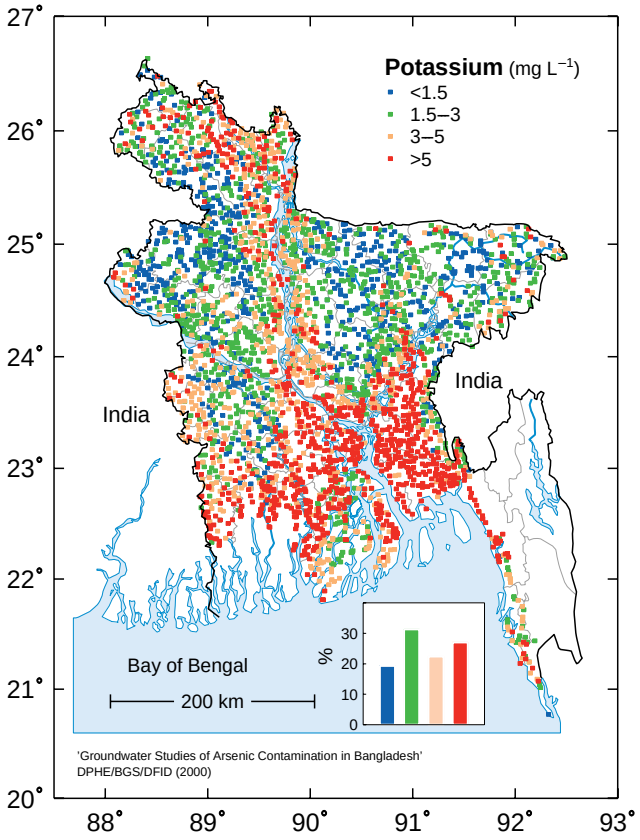

Figure 6.13. Spatial variation of potassium in groundwaters from the National Hydrochemical Survey.

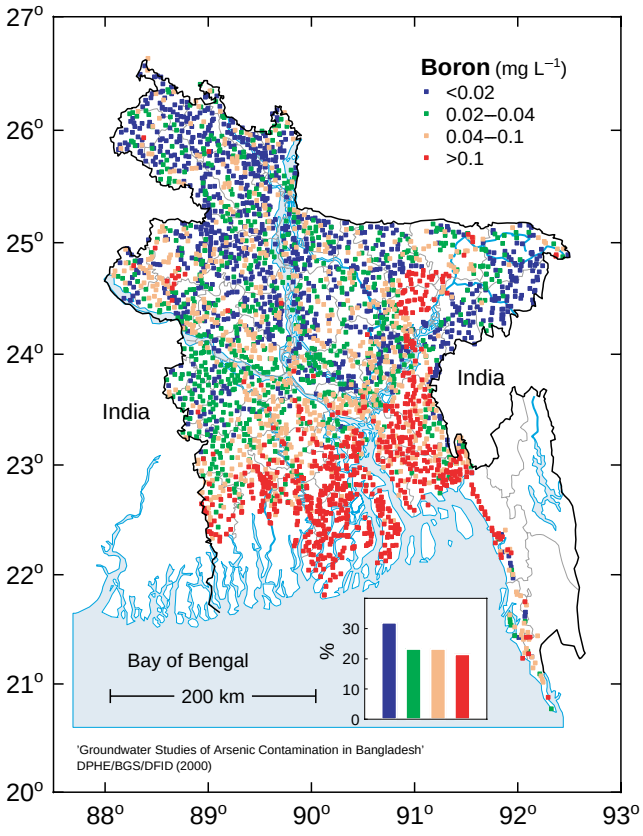

Figure 6.14. Spatial variation of boron in groundwaters from the National Hydrochemical Survey.

Relatively low concentrations of Na and B 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. In these areas, concentrations of these elements will be determined by the concentrations present in the recharge water (which will ultimately be determined by the sea-salt content of the rainfall and the extent of evapotranspiration), and by rock-water interactions, e.g. weathering of feldspars and clay minerals. Concentrations of K are correspondingly low in the Barind and Madhupur aquifers but are somewhat higher in the groundwaters from the Jamuna Valley and parts of the Tista Fan. This is believed to be due to weathering reactions.

The regional distribution of salinity in the deep aquifer is not known but DPHE has recently found some deep groundwaters to be saline as far north as Munshiganj and Manikganj.

6.10 SULPHATE

Sulphate concentrations are mainly very low in Bangladesh groundwaters. Concentrations from the National 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. Although the maximum values are high, the median values in both the shallow and deep groundwaters are low at <1 mg L^{-1}.

Figure 6.15 shows that concentrations are generally lowest in the south-west and southern parts of Bangladesh as well as in the Sylhet region of the north-east. The deep groundwaters from the southern coastal region 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). This would be expected to increase sulphate concentrations as a result of the high concentrations found in seawater (around 2700 mg L^{-1}). The low concentrations suggest that bacterial sulphate reduction has occurred. This is supported (Chapter 7) by limited $\delta^{34}S$ isotopic data from the Special Study Areas and low SO_4/Cl ratios relative to seawater in the more saline groundwaters of Lakshmipur *upazila*, indicating sulphate loss from solution. Sulphate reduction appears to have been an important process in both the shallow and deep aquifers. Sulphate reduction is indicative of highly reducing conditions since it tends to occur after Fe(III) reduction in the sequence of microbially-mediated redox reactions.

The SO_4 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,

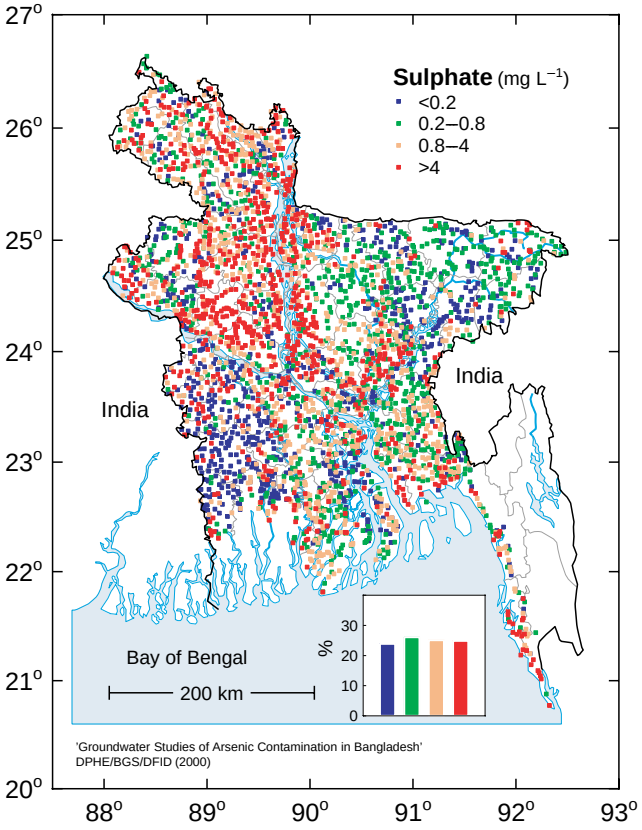

Figure 6.15. Spatial variation of sulphate in groundwaters from the National Hydrochemical Survey.

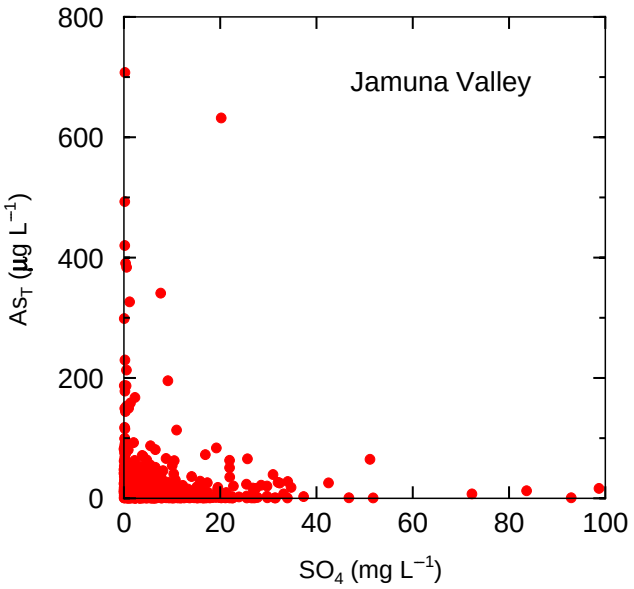

Figure 6.16. Arsenic concentrations plotted against sulphate concentrations in groundwaters from the Jamuna Valley based on data from the NHS.

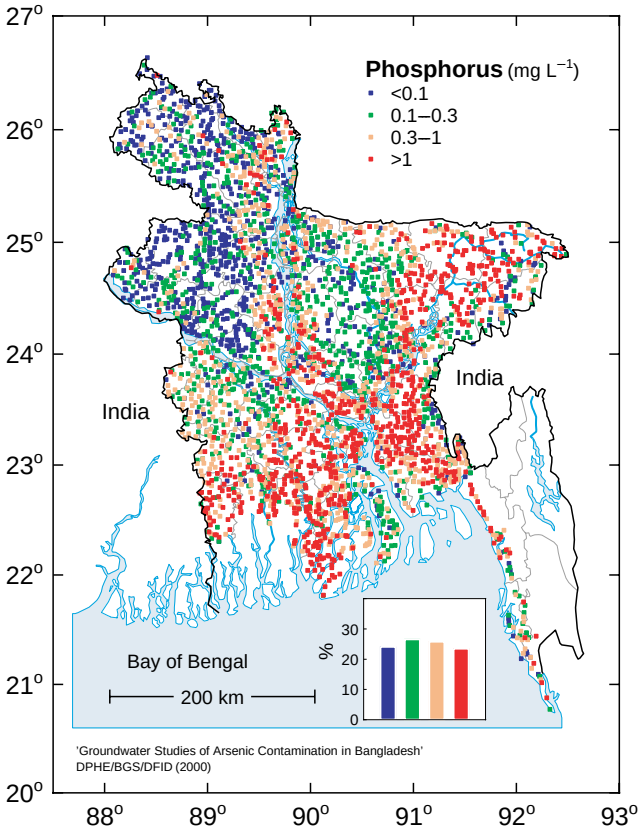

Figure 6.17. Spatial variation of phosphorus in groundwaters from the National Hydrochemical Survey.

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 (e.g. pyrite) in the aquifers. These processes are difficult to distinguish using the available geochemical data. 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 high-As tubewells of the Jamuna Valley, the groundwaters usually have low SO_4 concentrations (Figure 6.16). This suggests that even in this area, some sulphate reduction has taken place and that the reduction process has been accompanied by As mobilisation.

6.11 PHOSPHORUS

Phosphorus concentrations are quite variable in Bangladesh groundwaters. The P map shows some similarity to the As map. The concentration ranges found in the groundwaters are high by world standards: <0.1–19 mg L^{-1} in the shallow groundwaters and <0.1–6.1 mg L^{-1} in the deep groundwaters. Figure 6.17 shows that highest concentrations (>1 mg L^{-1}) are mainly found in groundwaters from 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 the southern coastal region have relatively high concentrations (often >1 mg L^{-1} P). The median concentration of P

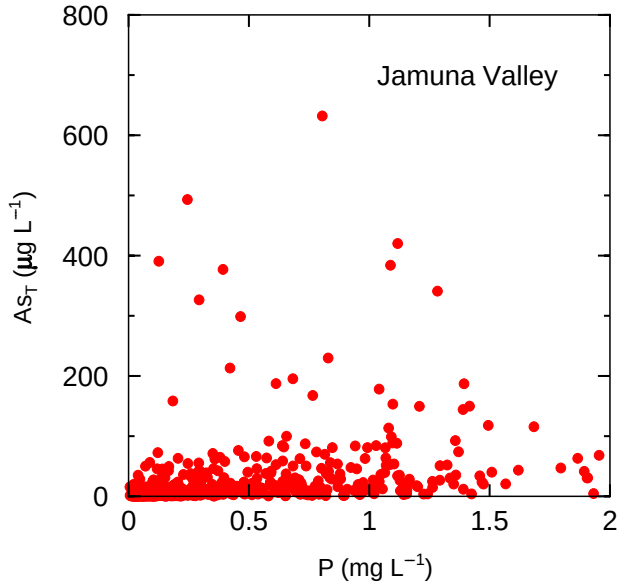

Figure 6.18. Arsenic concentrations plotted against phosphorus concentrations in groundwaters from the Jamuna Valley based on data from the NHS.

in As-contaminated (>50 µg L^{-1}) shallow groundwaters is 1.1 mg L^{-1}.

Some workers have attributed the high P concentrations to leaching of excess fertilisers from overlying soils (e.g. Acharyya et al., 1999, 2000). In view of the fact that high concentrations of P (>1 mg L^{-1}) are found in many groundwaters from both the shallow and deep aquifer, this is considered unlikely. Retardation of P by sediments is to be expected and P travel times to the deep aquifers should be significantly longer than the groundwater travel time itself. Dating of groundwaters from parts of the deep aquifer (Chapter 7) shows that these are 'old' groundwaters, of the order of thousands of years, hence they significantly predate fertiliser use. It is unlikely that fertilisers are a major source of P even in the shallow groundwaters.

Phosphorus in the groundwaters is believed to be derived mainly by desorption from, and dissolution of, iron oxides, although some is also probably derived from the oxidation of organic matter and from the dissolution of detrital apatite.

Dissolved P 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 responsible for the extensive arsenic mobilisation in Bangladesh groundwaters. However, the generally poor correlation between As and P in the groundwaters of the National Hydrochemical Survey and the presence of high phosphorus concentrations in many of the deep groundwaters which have low arsenic concentrations indicate that the geochemical processes are complex and that a number of factors are involved in arsenic release to the groundwater. The relationship between As and P is shown for one area, the Jamuna Valley, in Figure 6.18.

Table 6.16. Statistical summary and exceedances above WHO guideline values (GV) for groundwaters from the National Hydrochemical Survey analysed by ICP-MS

	Min	Max	Median	n	WHO GV	Exceedances	
	µg L^{-1}	µg L^{-1}	µg L^{-1}		µg L^{-1}	n	%
Al	4	27	8	16			
Be	<0.05	<0.05	<0.05	18			
Cd	<0.02	0.51	0.035	18	3	0	0
Ce	<0.005	0.587	0.0215	18			
Co	0.4	34.6	1.32	18			
Cr	<0.5	1.4	<0.5	16	50	0	0
Cs	<0.05	0.19	<0.05	18			
Cu	<1	8	<1	18	2000	0	0
Li	2	25	2.8	18			
Mo	<0.1	9.4	1.9	18	70	0	0
Ni	2.4	132	3.6	17	20	2	12
Pb	0.09	10.8	0.3	18	10	1	6
Rb	<0.1	10.2	0.45	18			
Sb	<0.02	0.16	0.03	18	5	0	0
Sn	<0.1	0.6	<0.1	18			
Tb	<0.005	0.01	<0.005	18			
Tl	<0.01	<0.01	<0.01	18			
U	0.03	11.6	2.365	18	2	10	56
V	<0.2	4.2	1.45	18			
Y	0.017	0.32	0.062	18			
Yb	<0.008	0.029	<0.008	18			
Zn	3	94	9.5	18			

6.12 Trace elements: ICP-MS data

In addition to the major and minor elements discussed above, a selection of trace elements were also measured in 18 samples from the National Hydrochemical Survey. The samples were selected on the basis of high Fe and Mn concentrations determined previously by ICP-AES. The data are therefore biased, but give an indication of water quality in the most metal-enriched groundwaters. Statistical summaries and exceedances with respect to WHO guideline values are given in Table 6.16 The results indicate that even in these samples, concentrations of most analysed trace metals are below recommended guideline values. The worst exceedances were for U, where 10 samples (56%) exceeded 2 µg L^{-1}. Two samples also exceeded the value for Ni and one sample exceeded for Pb, though the maximum Pb value was only 10.8 µg L^{-1}. The results indicate that few other trace metals in the ICP-MS range of analytes (with the possible exception of U) are likely to be of significant health concern.

6.13 BWDB Water-Quality Monitoring Network

Alongside the National Hydrochemical Survey, 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

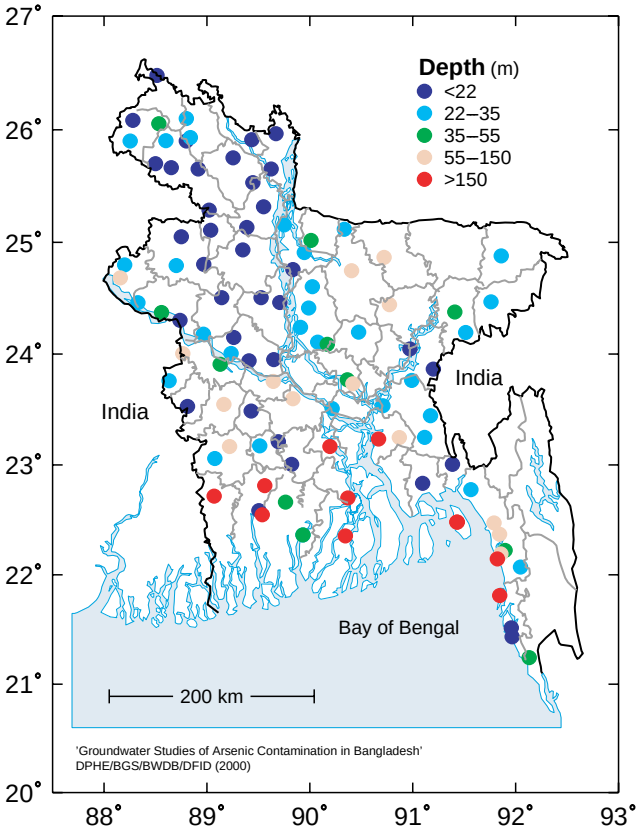

Figure 6.19. Distribution of well depths in the BWDB Water-Quality Monitoring Network survey.

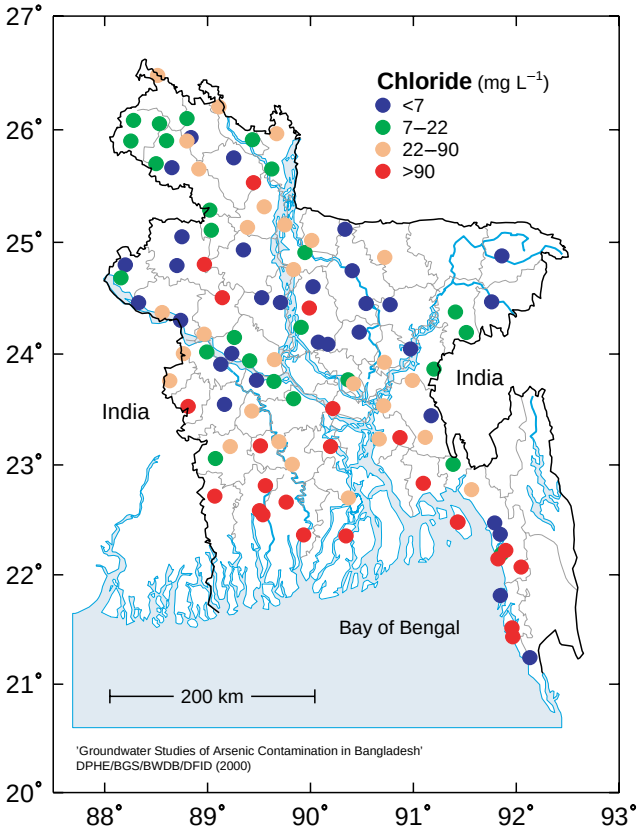

Figure 6.20. Chloride distribution in groundwaters from the BWDB Water-Quality Monitoring Network survey.

Tracts and Sunamganj in the north-east. The tubewells in the network are monitored by BWDB approximately bi-annually for water levels and a range of other chemical constituents. Sampling for this project was carried out during May–July 1998, except for 11 samples from the north-east which were collected in June 1999 due to inaccessibility problems the previous year. Analysis of major and trace elements was by ICP-AES and ICP-MS. Alkalinity was measured by titration with H_2SO_4 in the laboratory. In addition, chloride, fluoride and iodide were measured by AutoAnalyser.

The network includes wells with a large range of depths (7–610 m). The deepest tubewells are located mainly in the south, in Chittagong, Khulna and Barisal districts. Tubewells in the north-west are mainly shallow (<22 m). Some tubewells in Chittagong are also shallow. The range of well depths in the network are shown in Figure 6.19.

Elements measured in both the National Hydrochemical Survey and the BWDB Water-Quality Monitoring Network Survey include arsenic, calcium, magnesium, iron, manganese, boron, barium, strontium, sodium, silicon, phosphorus, potassium and sulphate. The spatial distributions of these elements have been plotted (see the *Hydrochemical atlas*). These parameters show general agreement with the distributions and concentration ranges seen from the National Hydrochemical Survey, except that the much lower sampling density fails to identify some patterns shown clearly by the National Hydrochemical Survey data. Maps for additional constituents measured in the BWDB Water-Quality Monitoring Network Survey (alkalinity, antimony, chloride, fluoride, iodide, lead, molybdenum, nickel, tin and zinc) are also given in the *Hydrochemical atlas*. The spatial distributions of some of these are discussed below.

6.13.1 Alkalinity

Alkalinity data based on BGS laboratory determinations have been included although we were aware that there was carbonate precipitation in some cases which may not have been fully included in the titration. Charge balances (excluding nitrate and ammonium) were sometimes poor as a result (9% of samples had a charge imbalance exceeding 1 meq L^{-1}). An approximate correction was applied to these samples by assuming that the charge imbalance reflected calcium carbonate precipitation. Despite uncertainties with the data quality, alkalinity (HCO_3) variations show some distinct regional patterns (see the *Hydrochemical atlas)* which closely follow the distributions of Ca, Mg, Sr and hardness. Highest alkalinities (HCO_3 >250 mg L^{-1}) are mainly found in the south-west. Intermediate values (125–250 mg L^{-1}) are found in the north-east and Jamuna Valley. Low alkalinities (<125 mg L^{-1}) are most typically found in the north-west (Tista Fan). As with the cations, the highest alkalinities are thought to reflect the presence of free carbonates in the soils and sediments.

6.13.2 Chloride

Concentrations of chloride in the surveyed samples have a

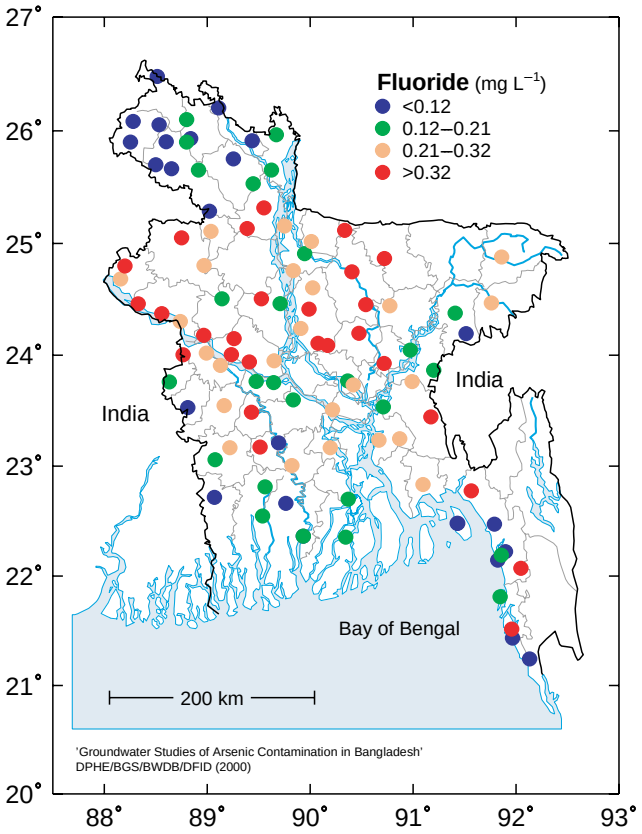

Figure 6.21. Fluoride distribution in groundwaters from the BWDB Water-Quality Monitoring Network survey.

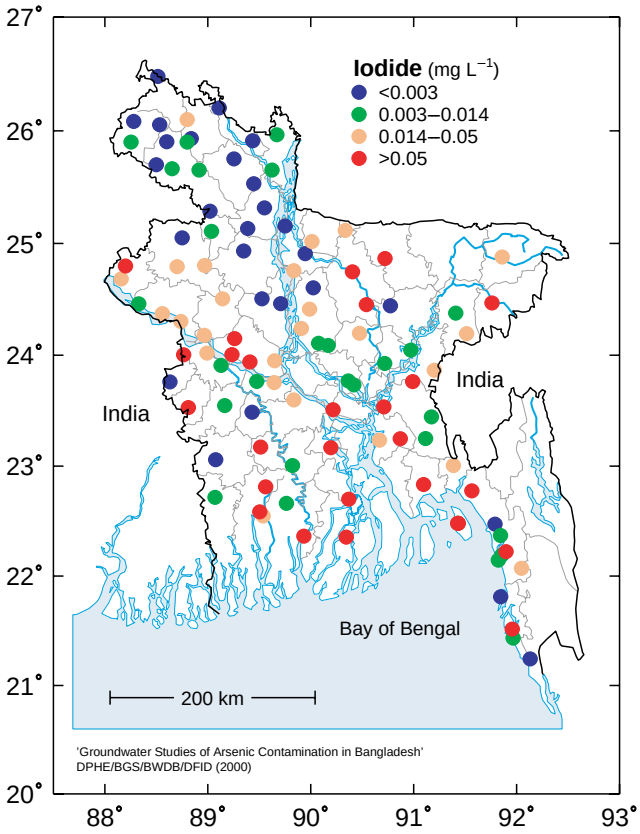

Figure 6.22. Iodide distribution in groundwaters from the BWDB Water-Quality Monitoring Network survey.

large range of 1.3–9140 mg L^{-1}. The distribution generally follows that of sodium with highest concentrations in the south of Bangladesh (both shallow and deep groundwaters), being indicative of salinity and marine intrusion (Figure 6.20).

6.13.3 Fluoride

Concentrations of fluoride in the groundwaters range between 0.01–0.73 mg L^{-1}. All these values are relatively low but the lowest concentrations are found mainly in north-west Bangladesh and the Chittagong coastal region (Figure 6.21). None of the samples exceeds the WHO guideline value for fluoride in drinking water of 1.5 mg L^{-1}. Indeed, many of the groundwaters are in the range where fluoride deficiency may become a problem without other forms of dietary fluoride. The low concentrations generally relate to the fact that groundwaters are dominantly of calcium-bicarbonate type and hence concentrations will be limited by fluorite solubility.

6.13.4 Iodide

Concentrations of iodide range between 0.4 μg L^{-1} and 5840 μg L^{-1}. Highest concentrations are scattered throughout the country but are typically high in southern Bangladesh where salinity is higher (Figure 6.22).

Iodine is an essential element for health and deficiency in the diet can lead to iodine-deficiency disorders (IDDs), the most common of which is goitre. Drinking water is only one source of dietary iodine, and is in most cases subordinate to that obtained from food. However, low iodine concentrations in drinking water may be indicative of low concentrations in the local environment in general (soils, local food crops) and may give a warning of the locations of IDD-prone areas. No WHO guideline value exists for iodide in drinking water as such guidelines represent maximum rather than minimum recommended values. However, in practice, endemic IDDs have been found in areas in developing countries where the drinking waters are typically less than 3–5 μg L^{-1}. In Bangladesh, only groundwaters from the north-west have such low concentrations (Figure 6.22). These areas may be susceptible to IDDs. Other parts of Bangladesh are considered to be less at risk from IDDs.

6.13.5 Trace metals: antimony, lead, molybdenum, nickel, uranium and zinc

All these elements show a considerable amount of spatial variability (see the *Hydrochemical atlas*). Among the more noteworthy variations are:

Sb: little discernible regional trend;

Pb: relatively low concentrations (<0.3 μg L^{-1}) in western Bangladesh, along the course of the Ganges (Nawabganj–Rajshahi–Pabna) and sporadic highs in Chittagong and the Tista Fan region;

Mo: relatively low (<0.1 μg L^{-1}) in north-west Bangladesh,

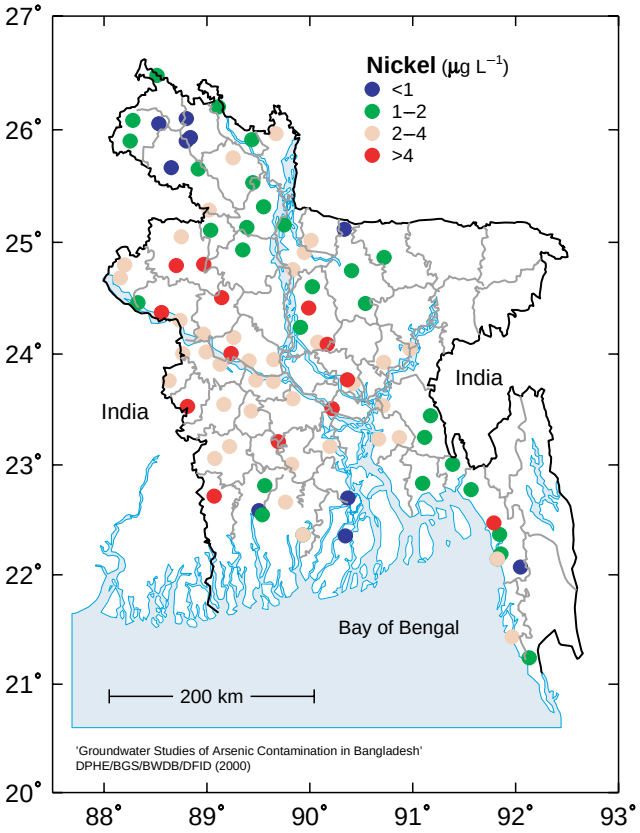

Figure 6.23. Nickel distribution in groundwaters from the BWDB Water-Quality Monitoring Network survey.

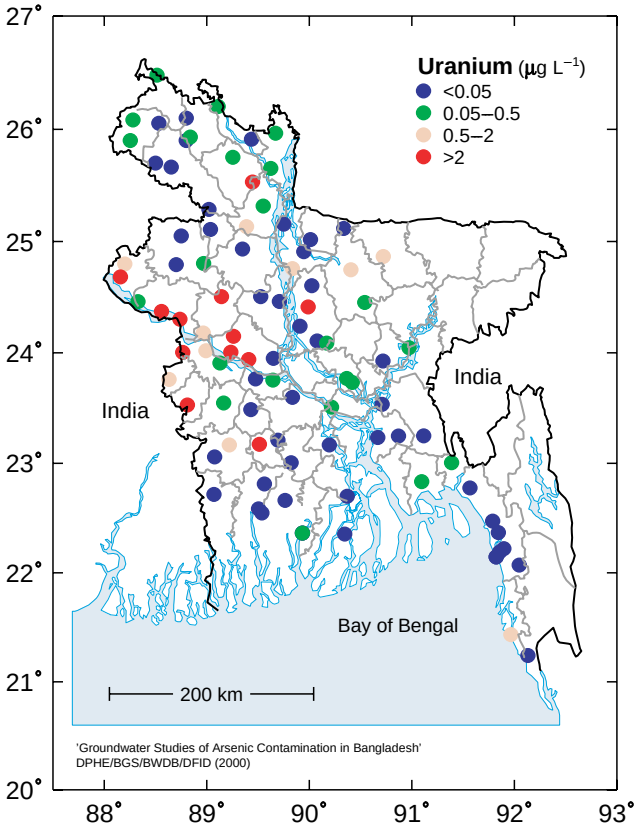

Figure 6.24. Uranium distribution observed in groundwaters from the BWDB Water-Quality Monitoring Network survey.

particularly the western part of the Tista Fan, variable elsewhere;

Ni: low concentrations (<2 µg L^{-1}) in the north-west (Tista Fan) and sporadically in the southern coastal area (Figure 6.23);

U: highest concentrations (>2 µg L^{-1}) in western Bangladesh (Ganges Floodplain and border districts) with usually low concentrations (<2 µg L^{-1}) elsewhere (Figure 6.24);

Zn: low concentrations (<10 µg L^{-1}) are most commonly found in south-western Bangladesh (Figure 6.25);

The low density of sampling in most cases precludes detailed interpretation of these trends. However, the distribution of Mo, with relatively low concentrations in north-west Bangladesh, to some extent reflects the distribution of As. As seen from the investigations in the Special Study Areas, Mo behaves in a similar way to As in the aquifers and often correlates with As. The variations observed in U concentrations in the BWDB Water-Quality Monitoring Network samples also mirror to some extent those from the Special Study Areas, where a greater proportion of high-U concentrations was found in groundwaters from Chapai Nawabganj. Many of the regional variations in these trace elements are also likely to reflect mineralogical (and hence trace-element) variations in the sediments as a result of varying sedimentation patterns and sediment provenance.

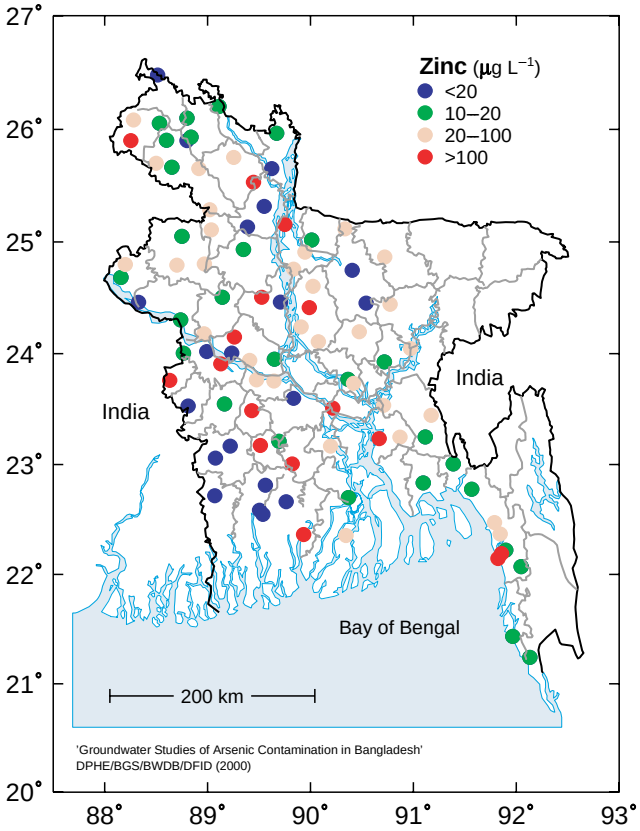

Figure 6.25. Zinc distribution in groundwaters from the BWDB Water-Quality Monitoring Network survey.

Table 6.17. Chemical data for groundwaters from deep tubewells in Dhaka city

Sample	Units	991545	991546	991547	991548	991549	991550	991551
Field code		RIP7501	RIP7502	RIP7503	RIP7504	RIP7505	RIP7506	RIP7507
Latitude		23.7497	23.726	23.7606	23.8017	23.7985	23.7405	23.7149
Longitude		90.3888	90.3852	90.3637	90.3597	90.4066	90.4072	90.4287
Location		Well S170A	Azimpur colony (pump 7)	Muhammadpur (pump 8)	Inside BIBM compound	Banani Pump (pump 5)	Circuit House	Bay Edabad
Ca	mg L^{-1}	31.4	50.7	24.3	15.4	15.4	16.5	59.2
Mg	mg L^{-1}	15.4	16.6	8.82	5.23	5.02	6.78	22.6
Na	mg L^{-1}	23	43	22	16	18	18	41
K	mg L^{-1}	2.0	5.6	1.8	2.3	1.7	1.7	2.5
SO_4	mg L^{-1}	11.5	31.6	2.8	0.6	1.2	6.4	34.6
As_T	µg L^{-1}	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Fe	mg L^{-1}	0.171	0.021	0.232	0.248	0.024	0.097	0.041
Mn	mg L^{-1}	0.674	0.027	0.017	0.066	0.021	0.058	0.223
Si	mg L^{-1}	38.8	25.4	35.7	40	37.9	38.9	37.2
B	mg L^{-1}	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Ba	µg L^{-1}	39	52	41	18	11	13	23
Sr	µg L^{-1}	189	482	179	118	110	107	377
P	mg L^{-1}	<0.1	<0.1	<0.1	0.1	0.1	<0.1	0.1
Al	µg L^{-1}	3	5	23	5	4	4	3
Li	µg L^{-1}	15.3	6	5.8	9.9	8.4	9.4	9.5
Be	µg L^{-1}	0.02	<0.01	0.01	0.05	0.01	0.03	0.02
Cd	µg L^{-1}	0.09	0.04	0.06	0.03	0.03	0.02	0.04
Co	µg L^{-1}	1.53	0.3	0.17	0.2	0.09	0.21	0.65
Cr	µg L^{-1}	<0.5	2.4	0.7	8.6	3.1	3.2	1
Zn	µg L^{-1}	13	20	5	97	13	6	6
Cu	µg L^{-1}	1	1	<1	2	2	1	11
Ni	µg L^{-1}	2.3	2.1	0.9	1.1	0.6	1	1.8
Pb	µg L^{-1}	0.21	0.28	0.37	0.23	0.2	0.17	0.42
Mo	µg L^{-1}	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Sb	µg L^{-1}	<0.01	0.01	0.02	0.06	<0.01	0.01	0.02
U	µg L^{-1}	0.3	0.42	0.16	0.02	0.03	0.04	0.97
Rb	µg L^{-1}	0.4	0.7	0.5	0.6	0.5	0.5	0.7
Cs	µg L^{-1}	0.005	<0.005	<0.005	0.005	<0.005	<0.005	<0.005
La	µg L^{-1}	0.006	0.012	0.013	<0.005	0.015	0.006	0.007
Ce	µg L^{-1}	0.015	0.022	0.02	0.007	0.023	0.008	0.009
Pr	µg L^{-1}	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Nd	µg L^{-1}	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Sm	µg L^{-1}	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Eu	µg L^{-1}	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Gd	µg L^{-1}	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Tb	µg L^{-1}	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Dy	µg L^{-1}	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Ho	µg L^{-1}	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Er	µg L^{-1}	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Yb	µg L^{-1}	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Lu	µg L^{-1}	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Sn	µg L^{-1}	0.2	<0.1	<0.1	<0.1	<0.1	0.3	0.2
Th	µg L^{-1}	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Tl	µg L^{-1}	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Tm	µg L^{-1}	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
V	µg L^{-1}	1.8	1.2	1.5	1.1	1.5	1.3	1.2
Y	µg L^{-1}	0.03	0.07	0.02	0.01	<0.01	<0.01	0.03

6.14 DETAILED CHEMISTRY OF DHAKA DEEP TUBEWELLS

In addition to these regional surveys, 7 groundwater samples were collected from the deep (Dupi Tila) aquifer of Dhaka city. The depths of the wells are unknown but are likely to exceed 200 m. Samples were collected in December 1999 and treated in the same way as the other samples, i.e. filtered and split into acidified and unacidified samples. Samples of the acidified aliquots were analysed by ICP-AES and ICP-MS and the results are given in Table 6.17.

The results indicate that these deep groundwaters are

of low salinity (Na <50 mg L^{-1}; B <0.1 mg L^{-1}; SO_4 0.6–35 mg L^{-1}) and have overall excellent inorganic quality. Concentrations of most trace elements are low to very low. In particular, As concentrations are all <0.5 μg L^{-1}. Iron concentrations are correspondingly low (<0.25 mg L^{-1}). Of the elements with WHO health-based guideline values, only Mn has any exceedances: one sample has a Mn concentration of 0.67 mg L^{-1} (Table 6.17). All other elements are substantially lower than the WHO guideline values. Concentrations of P are also uniformly very low (0.1 mg L^{-1} or less). Iron concentrations are generally much lower than in typical shallow Bangladesh groundwaters. There is no evidence of significant contamination with heavy metals.

As with evidence from elsewhere, the quality of groundwaters from the Dupi Tila aquifer is significantly better than that from the younger Holocene sediments of Bangladesh, despite the likelihood that a proportion of the groundwater from the Dhaka aquifers contains infiltrated river water.

In the deep Dupi Tila aquifer of Dhaka, potentially toxic trace elements are apparently not easily leached into solution (i.e. are not labile). Indeed, to some extent they are likely to already have been leached out due to a longer history of aquifer flushing and water-rock interaction. There are no signs in the trace-element data of serious contamination from the overlying, shallow aquifer which is heavily polluted in some parts of Dhaka. The most likely signs of possible early pollution are the relatively high Zn and Cr concentrations in the BIBM compound well. This appears to be the most reducing water on account of its relatively low SO4 and high Fe concentrations. Some of the low SO_4 concentrations may be due to sulphate reduction.

6.15 Comparison of the arsenic results with those from other large data sets

6.15.1 Background

Although we are aware that a large number of studies of arsenic contamination of groundwater have recently been undertaken in various places in Bangladesh, the results of these studies have either not been published, or the size of the surveys or the criteria for site selection do not make them suitable for comparison with the NHS database. The best surveys for such a comparison are therefore the large-scale screening surveys that have been, or are being, undertaken by NIPSOM-UNDP, NIPSOM-Columbia University, DPHE-UNICEF and BAMWSP. These surveys have been, or are being, mostly carried out using field-test kits either on 'randomly' selected wells or on a comprehensive (all well) basis.

The large number and high density of samples in these surveys tends to overcome the large amount of short-range variation present and compensates to some extent for the relative lack of precision of the test kits. Therefore the trends revealed from these surveys are expected to be quite reliable, especially for the more contaminated areas which are well above the detection limit of the kit being used. Indeed the use of field-test kits to establish such trends is an appropriate use of the kits. Establishing regional patterns from a large number of samples is far less demanding in terms of analytical accuracy than compliance testing where the result for each well is of great importance to the well owner.

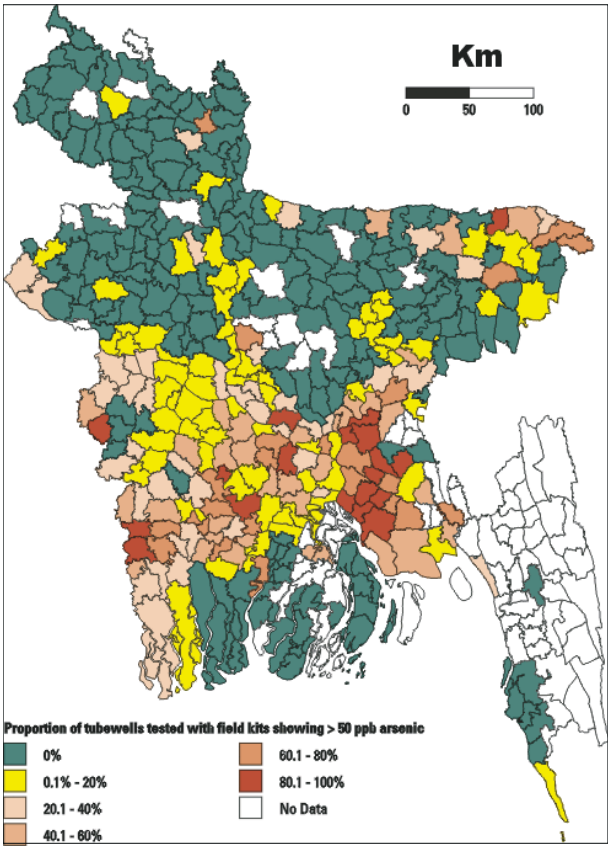

Figure 6.26. Results from the DPHE-UNICEF tubewell screening programme. Based on the analysis of some 51,000 tubewells using field-test kits (October, 1999).

Discussion of the comparison between these surveys and the DPHE/BGS National Hydrochemical Survey follows. The results of the 500 village NIPSOM-UNDP survey are not readily available and so cannot be analysed.

6.15.2 DPHE-UNICEF nationwide survey

The most comprehensive nationwide survey to date is that carried out by DPHE-UNICEF. The resultant map (Figure 6.26), based on the results of 51,000 analyses to October 1999, shows the percentage of wells exceeding 50 μg L^{-1} on a *upazila* basis. Aggregating data on a *upazila* basis imposes an implicit smoothing of the data and so it is best compared with either the NHS 50 μg L^{-1} probability map (Chapter 9, Figure 9.10(c)) or with the NHS smoothed arsenic map (Figure 6.4), both for shallow wells only. Even with the large number of wells sampled in the DPHE-UNICEF survey, this still represents only a small fraction of the total number of existing wells and so the representativeness of the resulting statistics and spatial patterns depend strongly on the quality of the randomisation.

The spatial patterns revealed in the DPHE-UNICEF map bear a close resemblance to the NHS As maps, with a concentration of highly-affected areas in south-east Bangladesh and sporadic highly-affected upazilas in south-cen-

tral Bangladesh (south-west of Dhaka) and on the western border with West Bengal.

Most of northern Bangladesh is shown to be relatively uncontaminated or not contaminated. Since the specified 'detection limit' of the field-test kits was 50 μg L^{-1} (and may have been somewhat greater in practice), the DPHE-UNICEF survey shows little resolution in northern Bangladesh. The NHS survey shows some variation across northern Bangladesh, albeit frequently below the 50 μg L^{-1} level, and indicates elevated concentrations in the low-lying parts of the Jamuna and northern Meghna valleys. The DPHE-UNICEF map indicates a greater density of contamination in the extreme north-eastern part of Greater Sylhet.

The greater sensitivity of the laboratory analyses used in the NHS also highlights the groundwaters from the older sediments of the Madhupur and Barind Tracts and the Tista Fan deposits of north-western Bangladesh as being significantly lower than those from the younger alluvial sediments of the Jamuna Valley. This is not so clear on the DPHE-UNICEF map.

6.15.3 BAMWSP (NESP) six *upazila* Phase I surveys

Phase I of the BAMWSP National Emergency Screening Programme (NESP) began in October 1999 by undertaking a comprehensive survey of wells in the following six *upazilas* (district in parentheses): Ishwardi (Pabna), Bheramara (Kushtia), Uzirpur (Barisal), Gopalganj Sadar (Gopalganj), Golapganj (Sylhet) and Hajiganj (Chandpur). The location of these *upazilas* is shown in Figure 6.27. The criteria for selecting these *upazilas* is not known. Hajiganj had already been comprehensively surveyed by BRAC. Plans for Phase II were initially to sample a further 60 *upazilas* but this is currently under review and is likely to be significantly reduced.

Some 49,000 wells from the six Phase I *upazilas* were tested using Merck field-test kits. Ownership (Government or non-Government) and well type (shallow and deep) were reported as well as whether they were contaminated or not (Table 6.18). There were just over six times as many non-Government wells as Government wells, showing the relative abundance and importance of private wells. On average, 5.6% of wells were not working at the time of sampling although the percentage varied from *upazila* to *upazila* (Table 6.19). The variation was from 13.6% in Uzirpur to 1.8% in Bheramara.

The number of contaminated wells varied from 10.7% to 97.8% and averaged about 50% (Table 6.19). There were deep tubewells in all *upazilas* but, as expected, they were concentrated in Uzirpur (Barisal) and Golapganj (Sylhet). The percentage of shallow tubewells contaminated did not differ much between Government and non-Government wells (Table 6.20) which is important since Government (DPHE) tubewells were mainly sampled in our NHS survey on the assumption that this was the case.

However, the NESP survey shows that there is a significant difference in the degree of contamination of Government and non-Government deep tubewells in some of the *upazilas*. On average, 4% of Government deep tubewells were contaminated against 22% of non-Government deep tubewells. This difference is greatest in Hajiganj (Chandpur) where 8% of Government deep and 62% of non-Government wells were found to be contaminated. This suggests that the construction of the two types of well may have been different (different depths, for example). Hajiganj is at the centre of the area where the shallow aquifer is highly contaminated, as seen from the statistics for the shallow wells (more than 95% contaminated). Perhaps the non-Government wells are actually shallower than the Government wells and situated in the deeper part of the shallow aquifer rather than in the 'deep' aquifer which is quite distinct in this part of Bangladesh. A similar conclusion can be drawn from the results for Gopalganj *upazila*. Lessons should be learned from these differences.

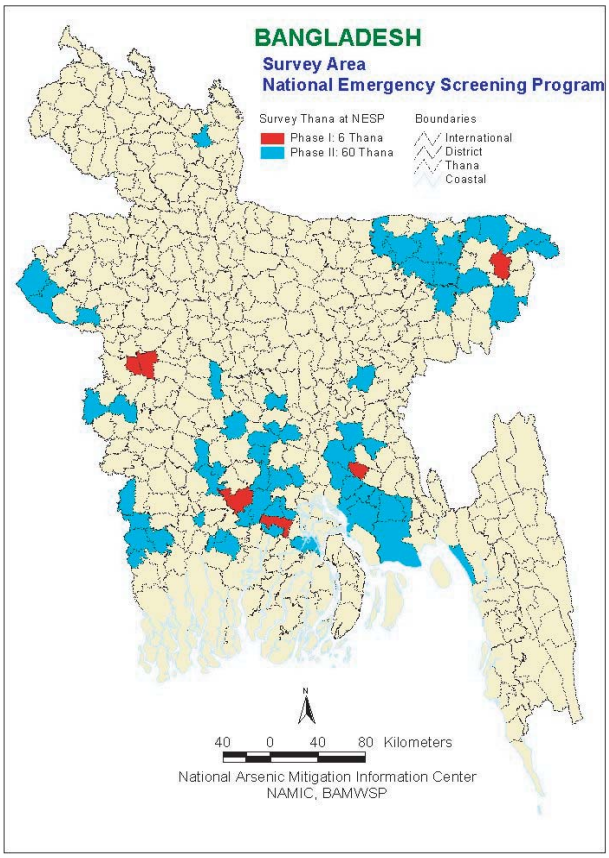

Figure 6.27. Location of the *upazilas* selected for comprehensive screening in Phases I and II of the BAMWSP National Emergency Screening Programme (NESP).

The majority of wells sampled in Uzirpur *upazila* (Barisal), which is in the southern coastal region of Bangladesh, were deep wells because of the presence of salinity in shallower horizons. Only 2% of these wells were reported as contaminated even though the shallow wells were mostly contaminated. This agrees with the results of the NHS where most of the deep wells sampled were from that region and showed a similarly low level of contamination. Some 20% of deep wells in Golapganj *upazila* in Sylhet district, both Government wells and non-Government wells, were contaminated. This is an area with a relatively low level of contamination in the shallow wells (10-14%) and so appears to reflect genuine contamination of the deep aquifer.

The NHS showed that one of the five wells from the

Table 6.18. Summary results of the 1999 NESP six *upazila* survey

Upazila, District	All wells			Deep wells		
	Tested	Arsenic-free	Arsenic-contaminated	Tested	Arsenic-free	Arsenic-contaminated
Government wells						
Uzirpur, Barisal	1141	102	773	1103	1025	21
Hajiganj, Chandpur	1272	40	1042	45	24	2
Gop. Sadar, Gopalganj	1824	61	1627	5	2	3
Bheramara, Khulna	807	539	246	3	2	1
Ishwardi, Pabna	907	767	102	19	18	0
Golapganj, Sylhet	671	559	88	90	69	17
Total	6622	2068	3878	1265	1140	44
Non-Government wells						
Uzirpur, Barisal	5039	344	4054	210	191	9
Hajiganj, Chandpur	8596	131	7999	13	5	8
Gop. Sadar, Gopalganj	5909	283	5349	7	0	7
Bheramara, Khulna	6249	4603	1590	33	20	9
Ishwardi, Pabna	8988	7876	987	24	19	2
Golapganj, Sylhet	7884	6917	745	524	359	107
Total	42665	20154	20724	811	594	142

Table 6.19. Extent of contamination of wells in the 1999 NESP survey of six *upazila*s

Upazila	Number of wells						% contaminated
	inoperative	operative	arsenic-free	<0.1 mg L^{-1}	0.1–1.0 mg L^{-1}	>1.0 mg L^{-1}	
Uzirpur	1032	6535	1666	686	4042	141	74.5
Hajiganj	792	9394	203	34	8861	296	97.8
Gop. Sadar	440	7354	353	508	6440	53	95.2
Bheramara	137	7392	5455	921	959	57	26.2
Ishwardi	197	9906	8797	298	785	26	11.2
Golapganj	320	9016	8048	602	365	1	10.7
Total	2918	49597	24522	3049	21452	574	Average 53%

Table 6.20. Percentage of wells contaminated according to owner and well type

Upazila	Government				Non-Government			
	Shallow wells		Deep wells		Shallow wells		Deep wells	
	Tested	% contam.	Tested	% contam.	Tested	% contam.	Tested	% contam.
Uzirpur	38	88	1103	2	4829	92	210	5
Hajiganj	1227	96	45	8	8583	98	13	62
Gopalganj Sadar	1819	96	5	60	5902	95	7	100
Bheramara	804	31	3	33	6216	26	33	31
Ishwardi	888	12	19	0	8964	11	24	10
Golapganj	581	14	90	20	7360	10	524	23
Total	5357	6622	1265	Average 4%	41854	42665	811	Average 19%

Sylhet district having a depth of greater than 150 m was contaminated, in that case quite severely (157 μg L^{-1}; 137 m depth). While the other four 'deep' wells were not contaminated at the 50 μg L^{-1} level, they all exceeded the 10 μg L^{-1} level. This contrasts with the NHS deep tubewell statistics from Barisal district: out of 50 deep tubewell samples in Barisal, only one exceeded 50 μg L^{-1} (54 μg L^{-1}; 331 m depth) and just a further two samples exceeded 10 μg L^{-1}. These results therefore point to systematic differences in the extent and nature of arsenic contamination of deep tubewells in different parts of the country. This probably reflects basic differences in the nature of the aquifers between the southern coastal region and the Sylhet region. The wells in Sylhet while 'deep' in terms of our defined depth interval (>150 m) actually tap the shallowest aquifer available. In the coastal region, the 'deep' wells tap a deep aquifer that is distinctly separate from the shallow aquifer in that area.

6.15.4 DPHE-UNICEF five *upazila* Community-Based Action Research Project surveys

As part of the DPHE-UNICEF Community-Based Action Research Project (CBARP), five *upazilas* were screened comprehensively for arsenic. The five *upazilas* (Districts in parentheses) were: Bera (Pabna), Jhikargacha (Jessore), Kachua (Chandpur), Sonargaon (Narayanganj) Manikganj sadar (Manikganj). This involved the testing of some 105,000 wells. The results for Manikganj were not available at the time of writing this report. The project began in March 1999 and involved the screening of some 788 villages in the four *upazilas*. The results for four *upazilas* are given in Table 6.21 and compared with those obtained by the NHS results in terms of the percentage of wells contaminated at the 50 μg L^{-1} level.

Plans are in place to tackle another 15 *upazilas* concentrated in southern Bangladesh.

6.15.5 Relationship with the numbers of arsenic patients identified

The large-scale screening surveys have also recorded the number of people showing symptoms of arsenic poisoning. In the DPHE-UNICEF four *upazila* survey, village health workers/community volunteers did the initial screening and physicians made the final diagnosis. A comparison of the results of such surveys with the arsenic concentrations in the tubewell water is obviously of great importance. It is commonly said in Bangladesh that 'the two maps do not agree'. Specifically, that relatively few patients have been identified from the highly contaminated region of south-east Bangladesh.

While such comparisons are best done on an individual household basis, the raw data were not available to us and so the only comparisons that could be made were based on the aggregated data.

Table 6.21 shows the results from the six *upazila* NESP survey and the four *upazila* DPHE-UNICEF survey. In the NHS survey, only 8 wells were sampled in these *upazilas* on average. This will inevitably lead to a relatively large uncertainty in the calculated percentage contamination and other statistics. On average, 68 tubewells were analysed from each district in the *upazilas* covered by these two surveys. Therefore district-wise statistics are also given. There is a compromise between aggregating enough samples to obtain reasonably reliable statistics and losing the spatial resolution required, especially when cross-correlating with epidemiological data.

The *upazila* by *upazila* comparisons for the DPHE-UNICEF survey are good (Figure 6.28) and better than when district-wise averages are used for the NHS results. The selected *upazilas* in this survey appear to be relatively high-arsenic areas within each of the given districts, except for Chandpur where the level of contamination appears uniformly high (given the definition of 'contaminated' used). This is also reflected in the *upazila*- and district-wise average As concentrations. The correlation between the NESP survey and the NHS survey (*upazila*- or district-based results) are not so good.

There is a poor correlation between the percentage of contaminated groundwaters and the density of patients (Figure 6.28). The most striking difference between the DPHE-UNICEF and NESP surveys is in the number of patients identified in Chandpur district, a district identified as highly contaminated in both surveys. The DPHE-UNICEF survey in Kachua *upazila* observed only 0.1 patient per 10,000 people while the NESP survey in neighbouring Hajiganj *upazila* found 62.1 patients per 10,000 population. The reasons for this dramatic difference need to be explored and raise doubts about the sampling methodology used for the various surveys. The differences may give some indication of why there is often a poor correlation between the number of patients observed and the level of groundwater contamination.

Table 6.21. Results from four *upazilas* from the DPHE-UNICEF CBARP survey, and the NESP six-*upazila* survey, including the number of patients identified with arsenic-related symptoms and relation to the arsenic contamination of the tubewell water

				% contaminated			Average concentration (μg L^{-1})	
Upazila	**District**	**Population (1999 est)**	**Patients per 10,000 people**	**DPHE-UNICEF**	**NHS (upazila)**	**NHS (district)**	**NHS (upazila)**	**NHS (district)**
DPHE-UNICEF CBARP survey								
Bera	Pabna	237,000	4.3	55	50	17	50	32
Jhikarghacha	Jessore	267,000	3.6	59	75	48	91	72
Kachua	Chandpur	333,000	0.1	97	90	90	267	360
Sonargaon	Narayanganj	301,000	7.1	62	67	23	172	35
NESP 6-upazila survey								
Uzirpur	Barisal	489,000	6.3	75	22	32	41	90
Hajiganj	Chandpur	300,000	62.1	98	100	90	413	360
Sadar	Gopalganj	344,000	9.0	95	100	79	275	183
Bheramara	Kushtia	170,000	23.5	26	71	28	303	111
Ishwardi	Pabna	280,000	8.0	11	40	17	128	29
Golapganj	Sylhet	270,000	0.4	11	0	18	3	27

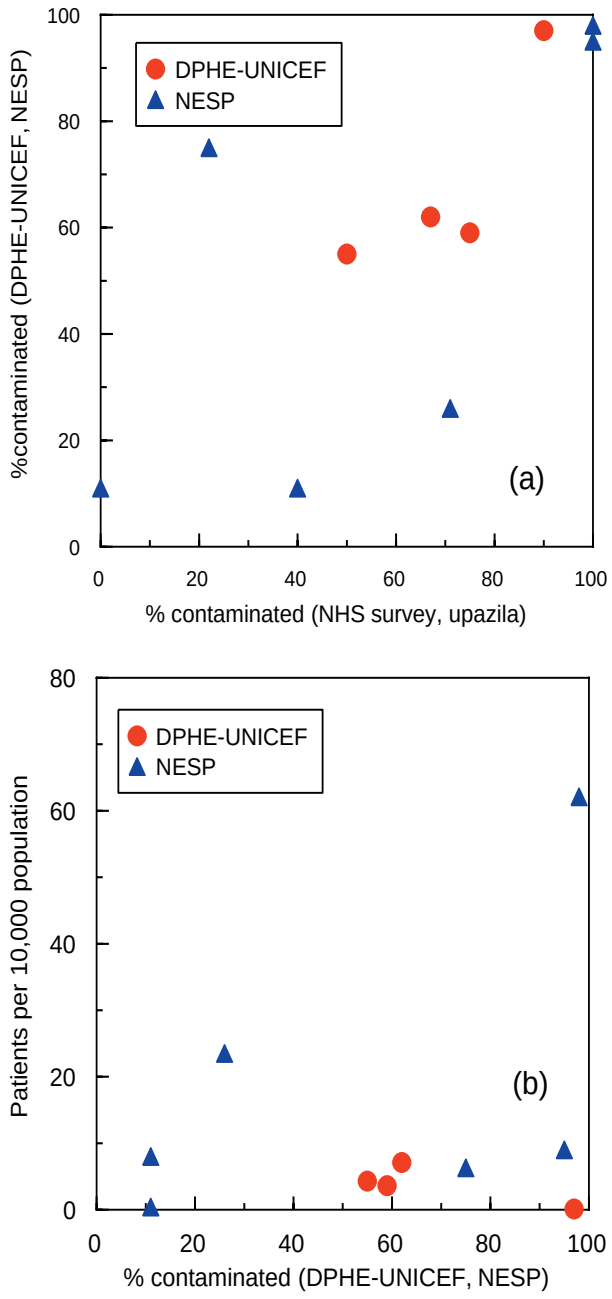

Figure 6.28. Relationships between observations of different surveys (a) level of contamination in the selected *upazila* between the NHS survey and the DPHE-UNICEF and NESP surveys, and (b) level of contamination in the DPHE-UNICEF and NESP surveys and the number of patients observed.

6.16 Microbiological quality

The parallel bacteriological water quality survey carried out on 1922 of the tubewells sampled in our 1998 survey showed that the the bacterial quality was not always adequate. Some 54% of samples failed the WHO guideline value for faecal coliforms, i.e. contained detectable coliforms (Hoque, 1998). The most significant causes of coliform contamination were found to be proximity of pit latrines and ditches. Well depth was found not to be a significant factor. Coliforms were detected in some of the deep groundwaters. The mechanism by which the deep wells become contaminated is not certain.

Ammonia-N was also found to be high in many samples with a median concentration of 1.0 mg L^{-1} (n = 1922) and a maximum of 7.5 mg L^{-1}. The ammonia concentrations tended to be high in the wells from southern Bangladesh including the deep tubewells from Barisal (Hoque, 1998).

6.17 Summary

High As concentrations are almost entirely restricted to groundwaters from the shallow aquifers (<150 m) which are composed of Holocene alluvial and deltaic sediments and are the dominant aquifers in Bangladesh. Groundwater As concentrations have a considerable range from <0.25 µg L^{-1} to 1670 µg L^{-1} and show some distinctive spatial trends, with the highest average values in the south and south-east. Some high concentrations are also recognised in groundwaters from the Holocene sediments of the Jamuna Valley. Localised hot spots are also identified in some generally low-As areas (e.g. Chapai Nawabganj, western Bangladesh). Of the shallow groundwaters from Holocene sediments, the north-west region (Tista Fan) has the most consistently low As concentrations.

Of the groundwaters investigated in the survey, 42% had As concentrations >10 µg L^{-1}, 25% >50 µg l^{-1}, 16% >100 µg L^{-1} and 0.06% >1 mg L^{-1}. Considering the shallow wells (≤150 m) alone, 46% exceeded 10 µg L^{-1} and 27% exceeded 50 µg L^{-1}.

In the shallow aquifers, considerable variations also exist in As concentrations with depth. Some of the shallowest groundwaters (<10 m) typically have low As concentrations probably as a result of more oxidising conditions.

Where sampled, deep groundwaters from 'deep' wells (>150 m depth) almost always have low As concentrations (95% <10 µg L^{-1}, 99% <50 µg L^{-1}, 3 samples out of 326 sampled being in excess of 50 µg L^{-1}). However, these deep wells were mainly from the southern coastal region and Sylhet in the north-east, and so are not necessarily representative of deep wells elsewhere in Bangladesh. The deep wells in Sylhet appear to contain more As than those from the southern coastal regions.

Phosphorus concentrations in Bangladesh groundwaters are high by world standards: <0.1–19 mg L^{-1} in the shallow groundwaters and <0.1–6.1 mg L^{-1} in the deep groundwaters. The highest concentrations (>1 mg L^{-1}) are mainly found in groundwaters from 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 the southern coastal region have relatively high concentrations (often >1 mg L^{-1} P).

Groundwaters from the Barind and Madhupur Tracts (Dupi Tila aquifer) have uniformly low As concentrations. These include the deep groundwaters from Dhaka city. Analysis of seven Dhaka WASA wells showed that all had <0.5 µg L^{-1} As. Deep wells from Dhaka city also had low concentrations of most other analysed trace elements. Concentrations of Cd, Cr, Pb, Ni, Sb and U were all substantially below WHO health-based guideline values. Only

Mn exceeded the guideline value (0.5 mg L^{-1}), with one sample having 0.67 mg L^{-1}.

The spatial pattern of As concentrations in the Holocene aquifer is believed to reflect a complex interrelationship between the redox characteristics, lithology of the aquifer and overlying sediments and history of groundwater flow. High concentrations in the south and south-east reflect the strongly reducing conditions in the aquifers in this area, poor permeability of overlying sediments, higher proportions of finer-grained material and iron oxides, slow rates of groundwater movement and lack of aquifer flushing.

In the north-central Jamuna Valley, groundwaters have very high concentrations of Fe (often greater than 10 mg L^{-1}) and Mn (up to 10 mg L^{-1}) relative to most of Bangladesh, and many have high SO_4 concentrations compared to the high-As groundwaters further south. The young sediments of the Jamuna Valley are thought to be undergoing active reduction but have not achieved such strongly reducing conditions overall as in the high-As areas of southern Bangladesh. This may be for a number of reasons: less fine-grained sediment at surface and hence less restriction of recharge and dissolved oxygen to the aquifers, shallow well depths and a relatively deep unsaturated zone compared to further south, and perhaps more active groundwater flow. Some of the higher SO_4 concentrations may be related to sulphide oxidation. However, if this is happening, it has not resulted in As mobilisation as As concentrations are low in the high-SO_4 groundwaters. By contrast, the high-As groundwaters (>50 μg L^{-1}) from the area have very low SO_4 concentrations, typically 1 mg L^{-1} or less, and indicate that these are more strongly reducing. This association of high As with low SO_4, as elsewhere in Bangladesh, precludes sulphide oxidation as the dominant cause of arsenic mobilisation, although groundwaters from a few tubewells may have been affected by this process.

Low As concentrations in groundwaters from the Tista Fan deposits of northern Bangladesh occur in generally relatively oxidising conditions with low overall Fe concentrations. These redox characteristics probably reflect the coarser grain-size of the Tista Fan sediments and lack of impermeable sediment cover, as well as more active flushing of the aquifer in this region.

The regional distributions of Fe and Mn in the groundwaters also strongly reflect redox controls. The Fe distribution shows some relationship with that of As, though it is weak in some places. Despite the strong redox control of Fe and Mn concentrations, these two elements have differing regional distributions reflecting differing redox potentials at which the respective reactions take place.

Distributions of Na, B and K largely reflect seawater influences, with greatest contributions from old seawater in southern Bangladesh (shallow and deep aquifers), the Sylhet Basin and the Atrai Floodplain north of the River Ganges. Potassium is also derived from mineral weathering reactions.

Distributions of Ca, Mg, Sr and to some extent Ba, reflect the distributions of free carbonates in the aquifer sediments and soils. Concentrations are generally highest in south-west Bangladesh.

Other elements of potential health concern besides As include Mn and in some more saline samples, B. In a small subset of National Hydrochemical Survey samples analysed for a wider suite of trace metals, U exceeded the WHO guideline value most frequently (10 samples, 56%). Nickel and Pb exceedances above guideline values were noted in a small percentage of samples, with maxima of 132 μg L^{-1} and 10.8 μg L^{-1} respectively.

Comparisons between the National Hydrochemical Survey and other surveys generally show good agreement in the regional patterns. Some differences exist in northern Bangladesh where the more sensitive analyses of the National Hydrochemical Survey reveals patterns with a low level of contamination which are not shown in the mass screening programmes.

The geographical distribution of patients so far identified does not appear to be closely related to the groundwater arsenic maps. The reasons for this are not clear and need further study.