10 Changes with time: groundwater monitoring

10.1 INTRODUCTION

The regional surveys of groundwater in Bangladesh have established significant variations in water quality both laterally and with depth. A further critical factor is the potential variation that can occur with time. Such variations may occur over very different timescales as a result of differing underlying controls. Short-term fluctuations in a given well, over periods of hours or days for example, may occur as a result of factors such as diurnal variations in pumping rate and duration. Variations over periods of months may result from the seasonal input of monsoon rainfall and changes in groundwater flow, for example. Monitoring in West Bengal has indicated that arsenic concentrations in tubewells are lowest during the months August-September (CGWB, 1999). Long-term variation over years or decades may result from factors such as a change in climate, land-use, abstraction rates or geochemical reaction. These differing scales of temporal variation have important implications for the screening and mitigation programmes and should be monitored carefully. The true variation also need to be separated from 'noise' resulting from sampling and analytical errors.

Scant reporting, much of it anecdotal, has so far concluded that temporal changes in arsenic concentrations have occurred in groundwaters from West Bengal and Bangladesh. Some reports (e.g. SOES/DCH, 2000) have suggested that 'deep' wells that were once arsenic-free are now arsenic-contaminated. What is not clear, is the nature of the variation (causes and timescales) and specifically, the amplitude of the variations. Some of the variation might feasibly be expected to be within the analytical error of the arsenic measurements. Monitoring requires high precision measurements if 'real' variations are to be distinguished from this noise. Furthermore, two situations have to be distinguished: (i) natural flow conditions (not influenced by abstractions), and (ii) pumped conditions where the abstraction of groundwater significantly changes the groundwater flow pattern.

One objective of the current project was to carry out a monitoring exercise of water levels and water quality in selected wells to assess the chemical variations with time and depth. As part of the detailed investigations in the selected three Special Study Areas, piezometers were installed to a range of depths in each of the three areas (Lakshmipur, Faridpur, Chapai Nawabganj) (Chapter 3). These, along with a selection of existing wells in the vicinity, have been sampled at approximately fortnightly intervals and provide time-series data for up to one year. This is a very short interval for assessment of temporal changes in water quality but provides a start to a process that should become a long-term investigation.

10.2 SAMPLING AND ANALYSIS

In all, 32 wells have been sampled in the Special Study Areas (Table 10.1). These included 15 piezometers, 14 other hand-pump tubewells and 3 dug wells.

10.2.1 Sampling and analytical protocol

Each well was sampled at approximately fortnightly intervals by DPHE R&D staff from Dhaka. Monitoring began after piezometer completion (from April 1999 in Chapai Nawabganj and Faridpur and June 1999 in Lakshmipur) and continued up until March 2000.

At each time of sampling, the wells were purged. This was reasonably straightforward for the shallow wells (around one pump stroke per foot of piezometer depth) but was much more difficult to achieve for the deep wells, although best efforts were made by hand pumping. Water levels were recorded in all the piezometers and dug wells but measurement was not routinely possible in the other tubewells due to lack of access via the well head.

At all sites, filtered samples (0.2 μm) were collected in 30 ml plastic bottles for chemical analysis. Each sample comprised two aliquots, one acidified (1% HNO_3) for analysis of As and other elements, and one unacidified for Cl analysis. During the early stages of monitoring, additional on-site investigation included measurement of SEC (specific electrical conductance) and water temperature. Water samples were returned to Dhaka and freighted to the UK in batches for analysis.

Analysis of As was initially by both ICP-AES (direct aspiration) and AFS with hydride generation. AFS analysis was carried out as for samples from the National Hydrochemical Survey and surveys in the Special Study Areas (Chapters 6 and 7). Cross-checks were made between the two As data sets and results for samples with high concentrations (>100 μg L^{-1}) were generally good (within 11% and mostly within 5%). Once the initial concentrations of As were determined for each well, subsequent analysis by AFS with hydride generation was only carried out where concentrations were expected to be low (in practice below around 100 μg L^{-1}) in order to cut costs.

Analysis of major cations, SO_4 and a range of trace elements was also made by ICP-AES. Chloride was determined by automated colorimetry.

During December 1999, an additional sampling of the piezometers and other monitoring wells was carried out for a wider range of chemical parameters, including redox measurements, stable isotopes, tritium and radiocarbon. Results of these investigations are reported separately in Chapter 7.

In the event, the Faridpur 10 m piezometer was found to be consistently dry and so no data have been produced for that depth. Yield of groundwater from the 50 m pie-

Table 10.1. Site details of monitored wells

Well name	Latitude	Longitude	Year constructed	Well type	Well depth (m)	Well location/owner
Chapai Nawabganj						
CPW1	24.5887	88.2554	1999	Piezometer	10	DPHE/Project
CPW2	24.5887	88.2554	1999	Piezometer	20	DPHE/Project
CPW3	24.5887	88.2554	1999	Piezometer	30	DPHE/Project
CPW4	24.5887	88.2554	1999	Piezometer	40	DPHE/Project
CHTW1	24.5887	88.2554	1989	Hand-pump tubewell	34	Primary School
CHTW2	24.5908	88.2592	1999	Hand-pump tubewell	20	Md. Sazzad Ali
CHTW3	24.5930	88.2568	1994	Hand-pump tubewell	15	Md. Sabed Ali
CHTW4	24.5874	88.2528	1992	Hand-pump tubewell	38	Alhaj Bashir Ali
CHTW5	24.5904	88.2587	1980	Hand-pump tubewell	34	Jam-e-Masjid
CHTW6	24.5878	88.2535	1984	Hand-pump tubewell	21	Md. Khorshed Ali
CHTW7	24.5906	88.2592	1997	Hand-pump tubewell	27	Md. Ashraful Islam
CDW1	24.5918	88.2409	1999	Dug well	8	Md. Dhulur Rahman
CDW2	24.5905	88.2578	1933	Dug well	9.1	Md. Ekramul Hoque Biswas
CDW3	24.5865	88.2541	1984	Dug well	8	Md. Mainul Islam
Faridpur						
FPW2	23.5870	89.8615	1999	Piezometer	20	DPHE/Project
FPW3	23.5870	89.8615	1999	Piezometer	30	DPHE/Project
FPW4	23.5870	89.8615	1999	Piezometer	40	DPHE/Project
FPW5	23.5870	89.8615	1999	Piezometer	50	DPHE/Project
FPW6	23.5870	89.8615	1999	Piezometer	150	DPHE/Project
FHTW1	23.5876	89.8610	1994	Hand-pump tubewell	41	Chairman
FHTW2	23.5866	89.8623	1996	Hand-pump tubewell	24	Md. Alef Mondal
FHTW3	23.5871	89.8623	1993	Hand-pump tubewell	46	Md. Haider Chukder
FHTW4	23.5876	89.8612	1999	Hand-pump tubewell	24	Health Centre
FHTW5	23.5869	89.8590	1996	Hand-pump tubewell	17	Md. Lokman Mollah
FHTW6	23.5881	89.8601	1998	Hand-pump tubewell	26	Md. Sekander Ali Pattader
Lakshmipur						
LPW1	22.9412	90.8433	1999	Piezometer	10	DPHE/Project
LPW2	22.9412	90.8433	1999	Piezometer	20	DPHE/Project
LPW3	22.9412	90.8433	1999	Piezometer	30	DPHE/Project
LPW4	22.9412	90.8433	1999	Piezometer	40	DPHE/Project
LPW5	22.9412	90.8433	1999	Piezometer	50	DPHE/Project
LPW6	22.9412	90.8433	1999	Piezometer	150	DPHE/Project
LHTW7	22.9412	90.8436	1999	Hand-pump tubewell	275	DPHE

zometer at Lakshmipur was also found to be very poor and variable. Hence results from that piezometer are to be viewed with caution.

10.2.2 QA problems

Monitoring of a large number of wells at regular intervals involves some significant logistical problems with sampling, labelling, recording, freighting, analysis and databasing. There is considerable scope for entry of errors throughout the procedure. Collection of monitoring data for the individual wells has highlighted some significant errors arising at all stages. While every effort has been made to remove obvious errors from our database, finding all of these is difficult and time-consuming and the data are not guaranteed to be error-free. Some of the following graphs of chemical data show incomplete time-series as a result of deletion of some of the glaring errors. Our experience indicates the absolute requirement for meticulous care with sampling, analysis, recording and reporting.

10.3 WATER LEVELS

Monsoon rainfall affects Bangladesh usually during the period July–September and this is the interval when most groundwater recharge occurs. Groundwater levels in the three study areas have varying responses to the monsoon, with the greatest impact being seen in Chapai Nawabganj and the least in Lakshmipur. The piezometers are not pumped between sampling periods and hence groundwater levels are essentially rest-water levels. The other wells in the monitoring network are used at other times, although all are hand-pump tubewells or dug wells and pumping rates are therefore minor.

10.3.1 Chapai Nawabganj

The hydrographs for the four Chapai Nawabganj piezometers (10–40 m depth) show a large seasonal fluctuation, with water levels ranging between around 1 m below ground level at the end of the monsoon period to around

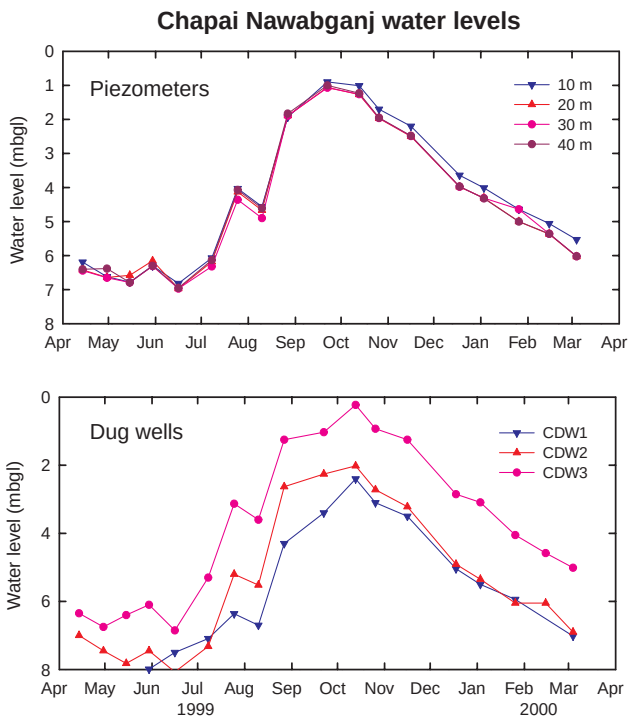

Figure 10.1. Temporal variation in water level (metres below ground level) at the Chapai Nawabganj monitoring sites.

7 m below ground level during the dry season. The seasonal amplitude of the fluctuation is therefore around 6 m. All piezometers have very similar responses which suggests close hydraulic connection between the sediment strata at the depths of abstraction (Figure 10.1). It is not thought likely that there is connection via the piezometer conduits themselves as care was taken during construction to ensure good sealing.

Groundwater levels in the Chapai Nawabganj dug wells showed very similar responses to the piezometers during the monitoring period (Figure 10.1) with amplitudes of variation also of the order of 6 m (groundwater-level range 0.2–8 m below surface). Absolute water levels are more disparate in the dug wells because of their greater spatial separation. Although all are less than 1 km apart, the distances are considerably greater than the spacing of the piezometers (typically within 3 m).

10.3.2 Faridpur

Water levels in the Faridpur shallow piezometers (20–50 m) also show a notable response to seasonal monsoon recharge, with rising groundwater levels during the period May 1999 to September 1999, a peak during September to November 1999 and recession thereafter (Figure 10.2). Water levels vary between around 2–6 m (amplitude 4 m). Hence the variation is less than for Chapai Nawabganj. The responses of all shallow piezometers are very similar, again suggesting hydraulic connection between the sediment strata over this depth range.

The trend in groundwater level in the deep 150 m piezometer at Faridpur (Figure 10.2) is notably similar to those from the shallow set (Figure 10.2). This suggests that

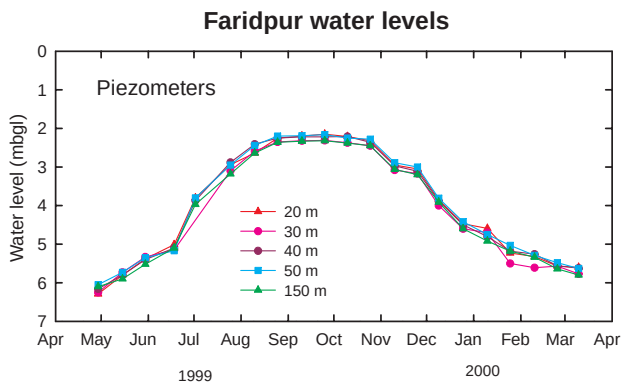

Figure 10.2. Temporal variation in water level (metres below ground level) at the Faridpur monitoring sites.

there may be a hydraulic connection between the shallow and 'deep' aquifers, although as discussed below and in Chapter 7, groundwater chemistry is notably different between the 20–50 m set and the 150 m piezometer.

The existing water-level data for the 150 m piezometer, like the shallow groundwaters, shows an apparent response to seasonal recharge. Radiocarbon data (Chapter 7) suggests that groundwater at this depth is significantly older than the shallow groundwaters (^{14}C in DIC of 51 pmc, with an apparent model age of around 2000 years). Hence, significant response to rainfall is not expected. This is a discrepancy which requires further investigation.

10.3.3 Lakshmipur

Groundwater levels in the piezometers from Lakshmipur are shallow, 1–2 m below ground level in the shallow groundwaters (10–50 m depth) and show a much smaller seasonal variation (Figure 10.3). Monitoring at Lakshmipur began later in the year (June 1999) than for the other two areas as these were the last piezometers to be drilled. Hence the pre-monsoon part of the hydrograph was not captured for 1999. However water levels were rising from June 1999 to September 1999. Groundwater level recessions appear to have begun around December 1999. The amplitude of the variation is typically about 1 m, albeit

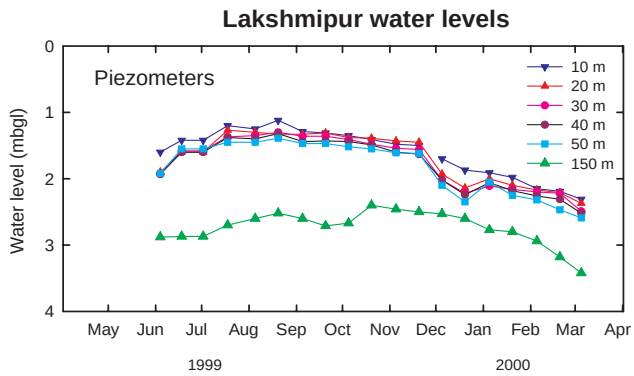

Figure 10.3. Temporal variation in water level (metres below ground level) measured at the Lakshmipur monitoring sites.

with only a 9-month period of monitoring.

Unlike Faridpur, the deep piezometer is very distinct from those at shallower levels and suggests hydraulic segregation between the shallow (10–50 m) and deep (150 m) aquifers. However, although absolute depths differ, the shapes of the respective profiles are quite similar and the deep piezometer shows a potential groundwater recession during November 1999 to March 2000. This may indicate some groundwater recharge, although a longer period of monitoring is required to be certain of the trends. Isotopic dating suggests that groundwater from this deep piezometer is largely 'old' water (^{14}C=28 pmc; Chapter 7) and does not contain significant modern recharge.

The lower absolute level of groundwater in the deep piezometer (around 3 m below ground level) was typically around 1.5–2 m below those in the shallow piezometers (Figure 10.3). This suggests that some downward leakage of groundwater to the lower (150 m) aquifer will occur if intervening sediments are sufficiently permeable. It must be remembered however, that the deep tubewells in Lakshmipur *upazila* were typically much deeper than 150 m and that this conclusion does not necessarily hold for greater depths. Indeed, notable variations in groundwater salinity with depth in Lakshmipur area suggest that strong groundwater stratification and poor hydraulic connectivity is more typical.

10.4 Arsenic

Results of the well monitoring in each of the three study areas are presented in Figures 10.4–10.6. As mentioned above, data for some sampling dates are missing because of suspicions about the quality of the data.

10.4.1 Chapai Nawabganj

As shown in Chapter 7, As concentrations in the groundwaters from the Chapai Nawabganj piezometers are relatively low at the shallowest depth (10 m), being generally <30 μg L^{-1}. They are much higher (250–350 μg L^{-1}) and comparable in the depth range 20–40 m (Figure 10.4). The low As concentrations in the shallowest piezometer probably reflect relatively oxidising conditions which facilitate adsorption onto precipitated iron oxides. The concentrations in the groundwaters from 20–40 m are high, but much lower than the extremes seen elsewhere in Chanlai, given that the piezometers are located in the heart of the Chapai Nawabganj 'hot spot'.

Neither the shallow (10 m) piezometer nor the deeper (20–40 m) piezometers showed any notable temporal trend in As concentrations during the period of monitoring. Concentrations were relatively low during the sampling in late August 1999 (at all depths) but this does not show an obvious trend with water level (Figure 10.4).

The shallowest piezometer with the lowest As concentrations showed no evidence of an increase with time during the sampling period, and all measurements were well below 50 μg L^{-1} (expanded graph, Figure 10.4).

Other monitored hand-pump tubewells from Chapai Nawabganj had variable absolute concentrations from 40–800 μg L^{-1}. The highest As concentrations were found in tubewells CHTW1 and CHTW4 which have well depths

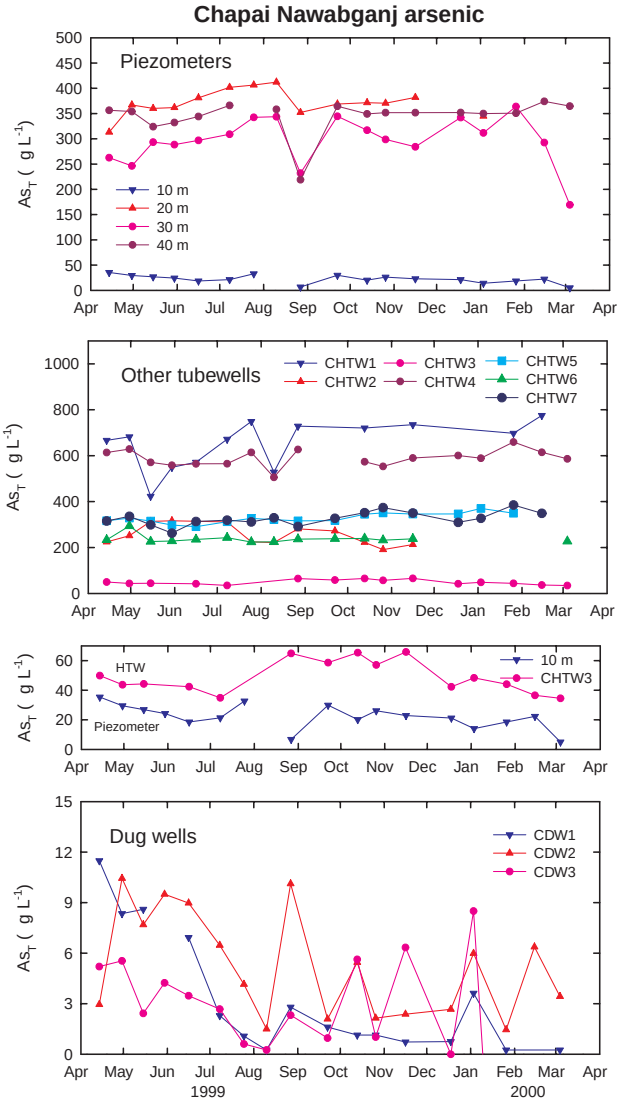

Figure 10.4. Temporal variation in As at the Chapai Nawabganj monitoring sites.

of 34 m and 38 m respectively. The other CHTW wells which are shallower than these have lower As concentrations, though only CHTW3 (15 m depth) has concentrations close to or less than 50 μg L^{-1}. The arsenic concentration at a given depth is therefore not the same in different tubewells with the sample region.

None of the additional tubewells sampled showed convincing evidence of increases or decreases of As concentration with time and there is no evidence of any response to seasonal recharge inputs. The expanded graph for the tubewell with the lowest concentration (CHTW3, Figure 10.4) shows variation between 35 μg L^{-1} and 66 μg L^{-1} and does show some apparent increase during the monsoon period. The depth of this tubewell is shallow (15 m) and this is probably the reason for the apparent variation. Shallow groundwaters are likely to be much more susceptible to seasonal changes in chemistry as a result of more active groundwater movement. Changes in concentration are also more discernible at low absolute concentrations. The concentration range of As in CHTW3 fluctuates around

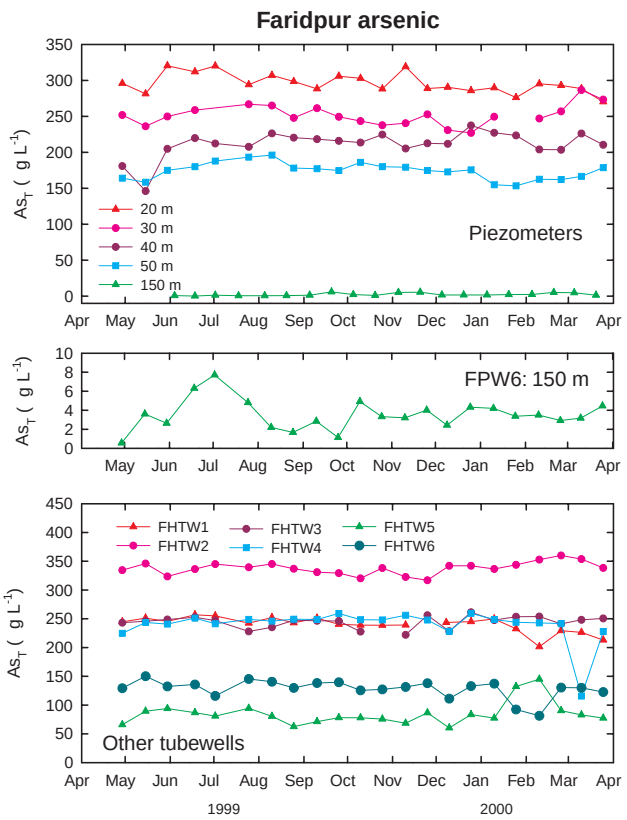

Figure 10.5. Temporal variation in As at the Faridpur monitoring sites.

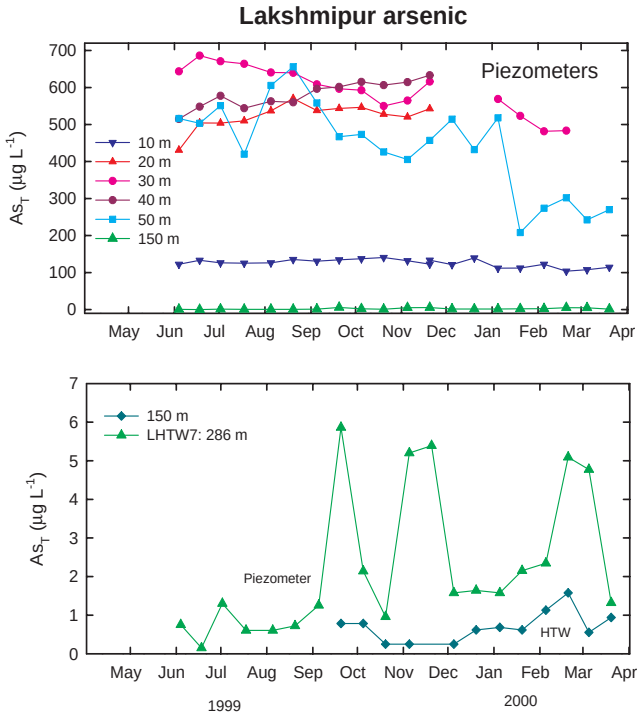

Figure 10.6. Temporal variation in As at the Lakshmipur monitoring sites.

50 μg L^{-1} (i.e. the national standard) and the variation serves to illustrate that some wells with concentrations close to the standard may be considered acceptable for drinking at some times but unacceptable at other times.

The three dug wells in the monitoring network at Chapai Nawabganj all have low As concentrations (Figure 10.4). Concentrations are very variable with 'spiky' temporal trends, although the range is only small 0.5–2 μg L^{-1}. Only 2 measurements exceeded the WHO guideline value of 10 μg L^{-1}. There is no evidence of As concentrations increasing with time, and no obvious evidence of a seasonal response to rainfall, despite the shallowness of these wells. One dug well had concentrations decreasing from April 1999 to July 1999 (pre-monsoon) but did not show any evidence of post-monsoon increase.

10.4.2 Faridpur

Arsenic concentrations in monitored wells from Faridpur were largely constant during the monitoring period (Figure 10.5). None of the shallow wells showed any seasonal response in As to rainfall. Concentrations were a little more variable during the early stages of sampling (May 1999) but this may be due to temporary disturbances in the groundwater chemistry following drilling.

In the shallow piezometers, As concentrations show a progressive decrease with depth, from maximum values at 20 m (ca. 300 μg L^{-1}) to minima at 50 m (ca. 160 μg L^{-1}). The profile may be explained in part at least by the occurrence of relatively high concentrations of oxalate-extractable As and Fe (denoting higher concentrations of labile As) at around 10 m depth (Figures 11.13 and 14, Chapter 11).

The 150 m piezometer had low overall concentrations during the monitored period (≤8 μg L^{-1}). The highest concentration was found during early July but the data are too limited to indicate whether or not this has any relation to the monsoon (Figure 10.5). Such rapid responses to monsoon recharge at this depth are considered unlikely.

Arsenic concentrations in the other hand-pump tubewells monitored at Faridpur were also largely constant (Figure 10.5). All are shallow wells and all exceed 50 μg L^{-1}. The highest As concentrations among these were found in tubewell FHTW2 (24 m depth) which had concentrations in excess of 300 μg L^{-1}.

10.4.3 Lakshmipur

The monitored set at Lakshmipur comprises the 6 piezometers and one adjacent deep hand-pump tubewell (286 m deep; screen at 275 m) nearby. As shown from the piezometer depth profiles (Chapter 7), groundwater from the 10 m piezometer has the lowest concentrations of the shallow set, with about 100 μg L^{-1} As. The temporal variation is minimal (Figure 10.6). Variations in the 20 m piezometer are also minimal, although concentrations exceed 500 μg L^{-1}. Variations are greater in the groundwaters from 30, 40 and 50 m depth. The 40 m piezometer appears to show a slightly increasing trend (around 19%) between June and November 1999, while the 30 m piezometer shows a decreasing trend (around 27%) over the period June 1999 to March 2000. Whether this variation is related to seasonal recharge effects or not is not known and requires further monitoring for proper assessment.

Variations in the 50 m piezometer are much greater with initially high concentrations of 400–650 μg L^{-1} (Figure 10.6) but with lower concentrations around 300 μg L^{-1} during February–April 2000. As noted above, this piezometer gives a very poor yield on pumping and the groundwater composition is therefore unlikely to be representative.

Figure 10.6 also shows an expanded plot of the deep 150 m piezometer which confirms its low As concentrations in the range 0.5–6 μg L^{-1}. High values were recorded in September and November 1999 and February–March 2000. The baseline concentration for this piezometer appears to be closer to <1–2 μg L^{-1}. A longer sequence of data is needed to indicate whether there are any seasonal or longer trends.

The 286 m deep hand-pump tubewell (Figure 10.6) also had uniformly low As concentrations of <2 μg L^{-1} during the period of monitoring.

10.5 Sodium and chloride

Only a limited number of other major and trace elements are discussed here. Sodium and chloride have been included as they provide important indicators of groundwater salinity and its variation with time. Sodium may also be affected by mineral reactions including ion exchange.

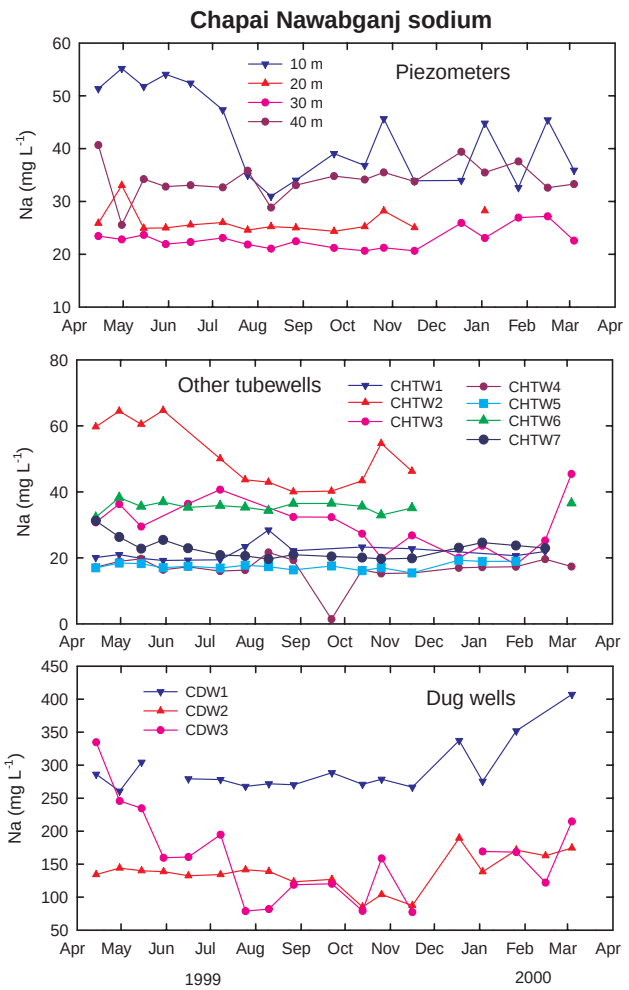

Figure 10.7. Temporal variation in Na at the Chapai Nawabganj monitoring sites.

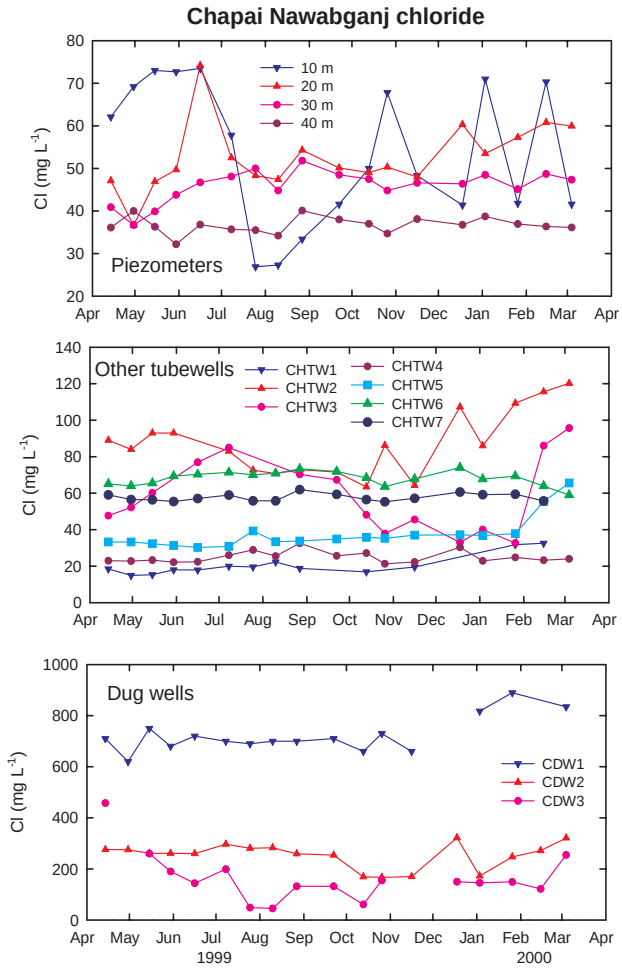

Figure 10.8. Temporal variation in Cl at the Chapai Nawabganj monitoring sites.

10.5.1 Chapai Nawabganj

In all monitored groundwaters from Chapai Nawabganj, the greatest variations and, for the most part highest concentrations, were seen in the shallowest wells. These were the 10 m piezometer, tubewells CHTW2 (20 m) and CHTW6 (21 m) and all the dug wells. This reflects the greatest influence of surface processes at shallow depths. In the zone near the water table, groundwater movement is likely to be most active, impacts of groundwater recharge and pollution inputs more immediate, and effects of variations in evaporation greatest. These are all thought to be influential controls on the groundwater chemistry of the shallow groundwaters, although the variations in absolute concentrations in the tubewells are not large. Concentrations of Na in the tubewell waters vary largely between 20–60 mg L^{-1} and in Cl between 20–70 mg L^{-1} (Figures 10.7 and 10.8). By contrast, concentrations in the open dug wells are generally much higher (Na up to 400 mg L^{-1}; Cl up to 900 mg L^{-1}) and reflect a more pronounced effect of evaporation and/or pollution.

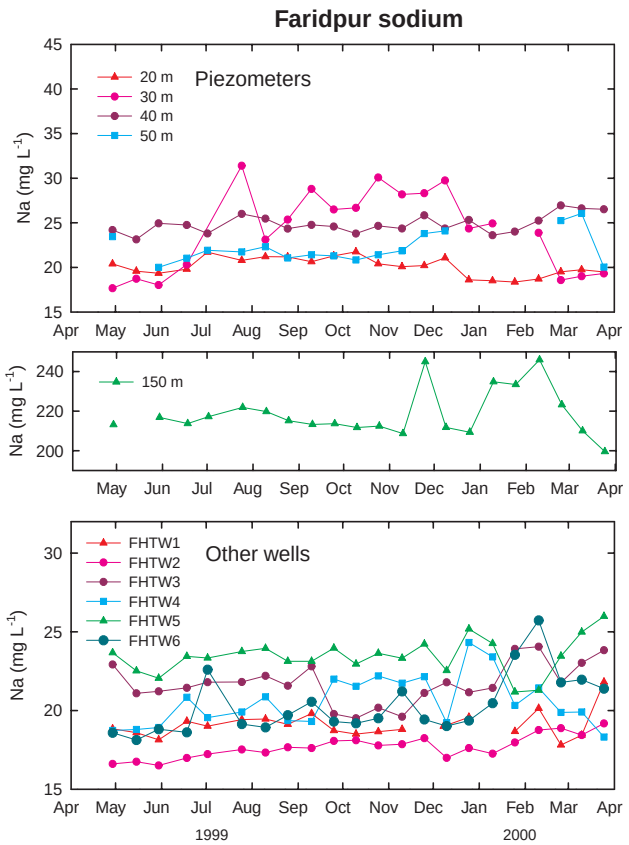

Figure 10.9. Temporal variation in Na at the Faridpur monitoring sites.

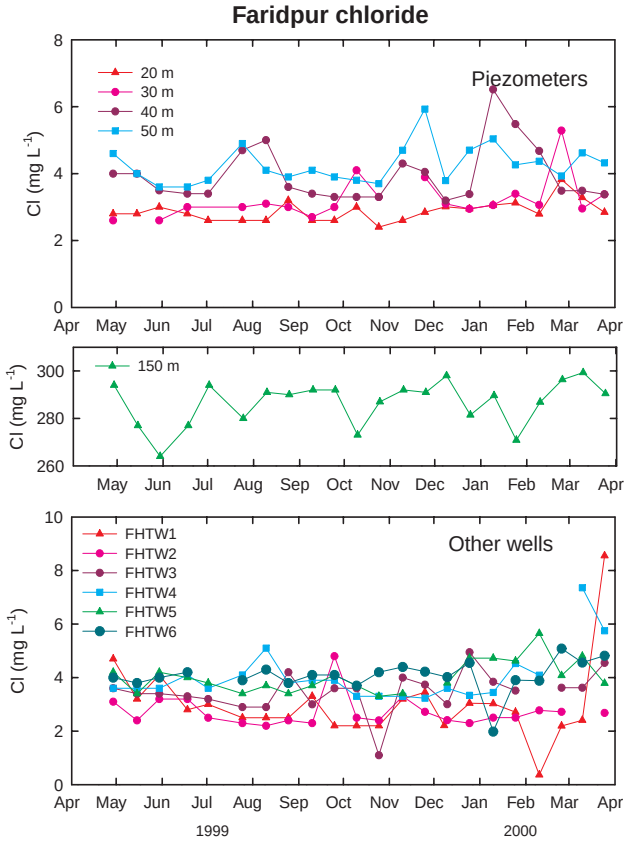

Figure 10.10. Temporal variation in Cl at the Faridpur monitoring sites.

10.5.2 Faridpur

Variations in Na and Cl in the Faridpur wells show some minor variations (Figures 10.9 and 10.10) but little or no evidence of seasonal trends. The only discrepancy is the slight increase in Na concentration in the 30 m piezometer over the period July–December 1999 (range 20–30 mg L^{-1}), although the Cl concentrations remained very low and stable (around 3 mg L^{-1}) over this interval. Concentrations in the deep 150 m piezometer showed no temporal trend, concentrations being in the range 200–250 mg L^{-1} for Na and 260–300 mg L^{-1} for Cl.

10.5.3 Lakshmipur

Concentrations of Na and Cl were remarkably constant in all monitored wells at Lakshmipur during the sampling period. In the shallow piezometers, concentrations generally showed a progressive increase with depth, reflecting the increasing salinity of the groundwaters at depths greater than about 20 m (and hence the dominance of tubewells of less than 20 m depth in the region; Chapter 7). There is no apparent seasonal effect relating to the monsoon. The trends for the deep tubewells reiterate the considerable salinity variations with depth at Lakshmipur, with high salinity in the 150 m piezometer, and remarkably fresh groundwater (Na around 35 mg L^{-1}, Cl around 10 mg L^{-1}) in the 286 m tubewell LHTW7 (Figures 10.11 and 10.12).

10.6 Sulphate

Sulphate is discussed here in order to investigate the evidence for oxidation of sulphide minerals in the aquifer, particularly close to the water table, and its potential effects on the concentrations of, and variations in, As in the groundwaters.

10.6.1 Chapai Nawabganj

In all cases, highest concentrations of SO_4 in the Chapai Nawabganj groundwaters were found at shallow depths

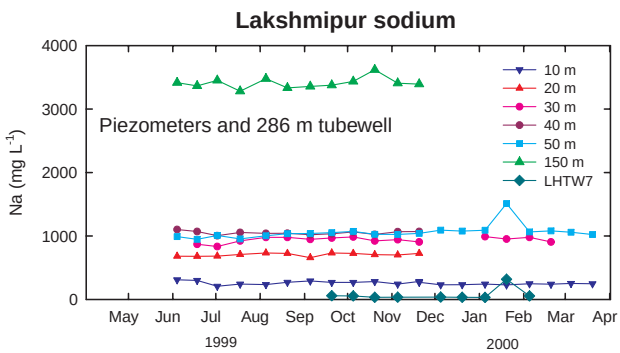

Figure 10.11. Temporal variation in Na at the Lakshmipur monitoring sites.

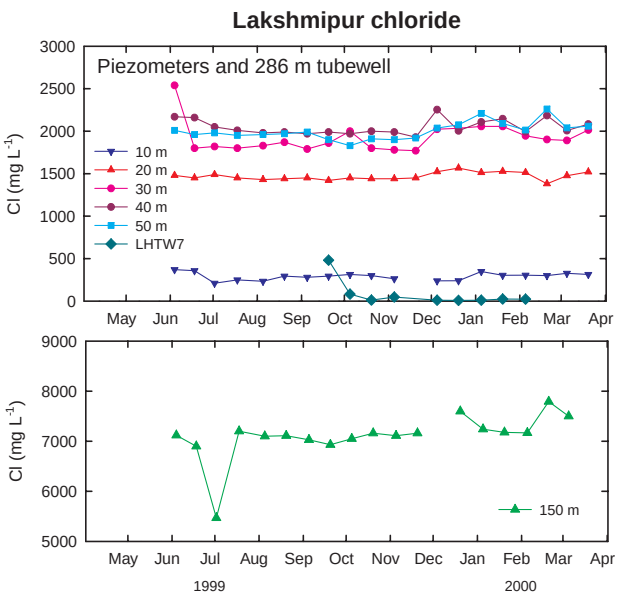

Figure 10.12. Temporal variation in Cl at the Lakshmipur monitoring sites.

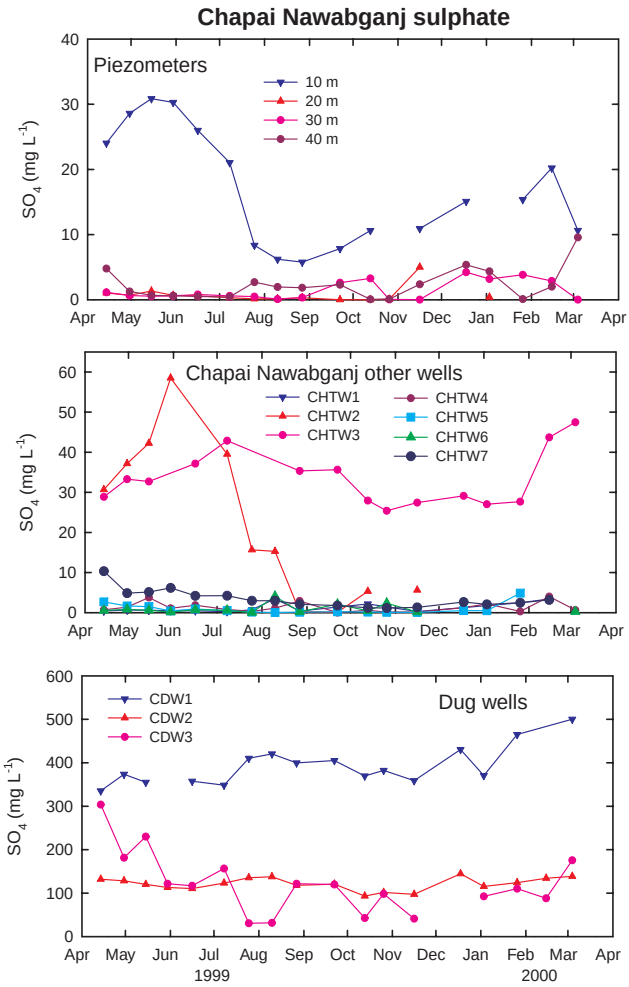

Figure 10.13. Temporal variation in SO_4 at the Chapai Nawabganj monitoring sites.

(Figure 10.13). Concentrations greater than 5 mg L^{-1} are largely restricted to the groundwaters from the 10 m piezometer, tubewells CHTW2 (20 m) and CHTW3 (15 m) and the dug wells. As noted in Chapter 7, the dug wells have by far the highest SO_4 concentrations, often in excess of 100 mg L^{-1}. These are also relatively oxidising with detectable dissolved oxygen. The shallow tubewells (and to some extent the dug wells) show pronounced seasonal trends which reflect variations in recharge, with minima around the period August–October 1999. This effect is probably the result of dilution from modern recharge. Sulphate present in the shallowest groundwaters during the dry periods is likely to be partly picked up from oxidation of sulphide minerals. As discussed in Section 10.5 and Chapter 7, the much higher concentrations in the dug wells probably reflect a combination of oxidation, pollution and evaporative concentration processes.

Concentrations of SO_4 in the 20–40 m piezometers and the other tubewells with depths greater than 20 m are typically much less than 5 mg L^{-1} (Figure 10.13). Concentrations in the piezometers at 30 m and 40 m rise slightly (to around 5 mg L^{-1}) over the period December 1999 to February 2000, possibly as a result of falling groundwater levels. Further monitoring is needed however, to assess whether this has any significance over the longer term.

The lack of correspondence between SO_4 and As concentrations in the Chapai Nawabganj groundwaters during the period monitored is significant and provides no support for the hypothesis that As release is related to pyrite oxidation.

10.6.2 Faridpur

Concentrations of SO_4 are low in the groundwaters from most of the Faridpur monitored wells, as concluded from the surveys outlined in Chapter 7. Concentrations <1 mg L^{-1} are typical. Values up to 10 mg L^{-1} were recorded in the 30 m piezometer (Figure 10.14), with a maximum during the beginning of the monsoon (July 1999) and a gradual decrease thereafter. Concentrations are most variable in the 50 m piezometer (up to 12 mg L^{-1}) with maxima in November 1999. Rising concentrations may correspond with the end of the monsoon and resulting recession of groundwater levels. The increase in SO_4 concentrations in the groundwater from this piezometer is not matched by increasing As concentrations.

Concentrations of SO_4 in the other monitored tubewells (FHTW wells; Figure 10.14) have low concentrations but very spiky trends. At such low concentrations, the extent of analytical error is uncertain. Certainly no seasonal trends can be discerned from the data.

10.6.3 Lakshmipur

The shallow groundwaters from the Lakshmipur piezometers have dominantly low SO_4 concentrations (<10 mg L^{-1}) and, as noted for other Lakshmipur groundwaters in Chapter 7, much lower than expected from equivalent Cl (and Na) concentrations. The low values reflect loss of SO_4 from solution by bacterially-mediated reduction reactions. Despite this dominant process, the SO_4 concentrations (as with other major elements in the

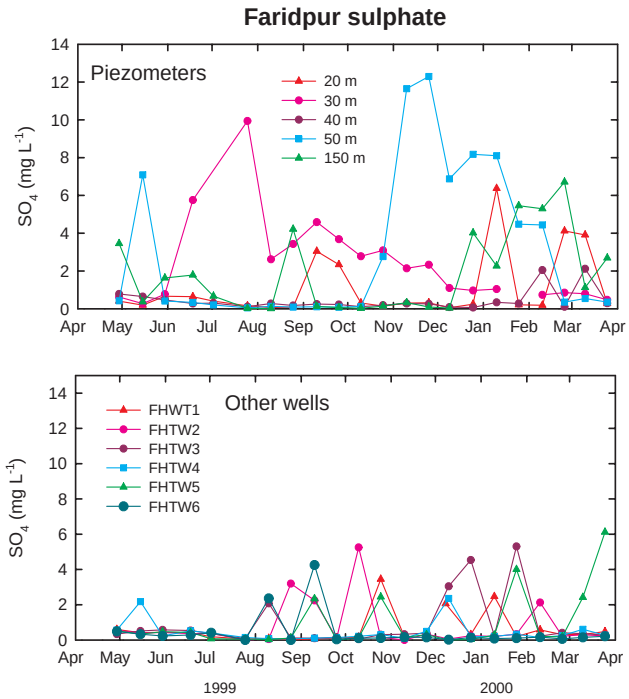

Figure 10.14. Temporal variation in SO_4 at the Faridpur monitoring sites.

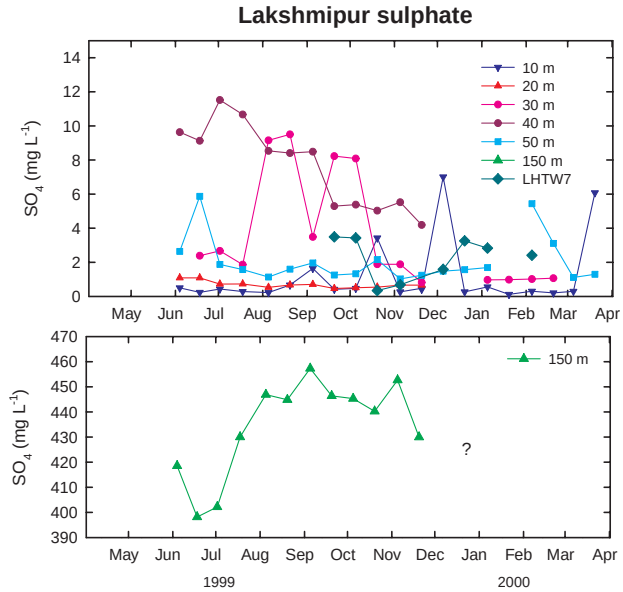

Figure 10.15. Temporal variation in SO_4 at the Faridpur monitoring sites.

Lakshmipur piezometers) reflect to some extent groundwater salinity. Concentrations increase progressively with depth going from 10 m to 40 m bgl.

Piezometers at 30 m and 40 m have apparent maxima over the monsoon period, though there is no apparent increase during this time in the shallowest piezometers. The reasons for these variations are not clear from the existing data and a longer period of monitoring is required to determine the main processes.

Sulphate concentrations in the 150 m piezometer lie in the range 400–600 mg L^{-1} range with a distinct increase during the monsoon period (Figure 10.15). The reason for this is not clear. It did not appear to be a simple consequence of ingress of sea water as Cl concentrations did not show a coincident increase.

10.7 PHOSPHATE

Phosphate is discussed briefly here because of the potential diagnostic use of depth information in determining the significance of pollutants such as fertilisers in contributing P to the groundwaters.

10.7.1 Chapai Nawabganj

Concentrations of P in the monitored network at Chapai Nawabganj are considerably higher in the tubewell waters than the dug wells, with concentrations up to around 1 mg L^{-1} (Figure 10.16). Concentrations in the dug wells were mostly <0.2 mg L^{-1} and are not shown. Trends are somewhat spiky and some of the variation perhaps reflects unresolved sampling and analytical errors. However, in the early part of monitoring of the piezometers (April–August 1999), concentrations appeared to progressively decrease in the interval from 10–40 m depth. Later variations are less clearly stratified, with maximum concentrations observed in the 40 m piezometer. The trends do not provide convincing evidence for a pollutant source including a fertiliser source. The piezometers at Chapai Nawabganj are located at a Primary School in the centre of Chanlai where impacts of fertiliser from local fertiliser applications are expected to be minimal. Therefore, in this case, the leaching of fertiliser phosphate is unlikely to be a main driving force for the development of high arsenic groundwaters.

In the other monitored sites (CHTW wells), concentrations are variable between wells with no consistent depth relations. The shallowest wells have both the highest (CHTW6; 21 m) and lowest (CHTW3; 15 m) concentrations (Figure 10.16). The P data do not provide unequivocal evidence for the dominant sources of phosphate.

10.7.2 Faridpur

Concentrations of P in the monitored wells at Faridpur are generally high (often 1–3 mg L^{-1}; Figure 10.17). The profiles show no discernible temporal trend. Highest concentrations in the shallow piezometer set are found at the 40 m depth, lowest at 20 m. This does not suggest a surface-derived pollutant source since concentrations would be expected to decrease with depth. The highest concentrations among the other monitored wells are from FHTW1 (41 m depth). The deep 150 m piezometer has consistently low P concentrations (<0.2 mg L^{-1}; Figure 10.17).

10.7.3 Lakshmipur

Shallow groundwaters from the Lakshmipur piezometers have generally high P concentrations (1–2 mg L^{-1}) (Figure

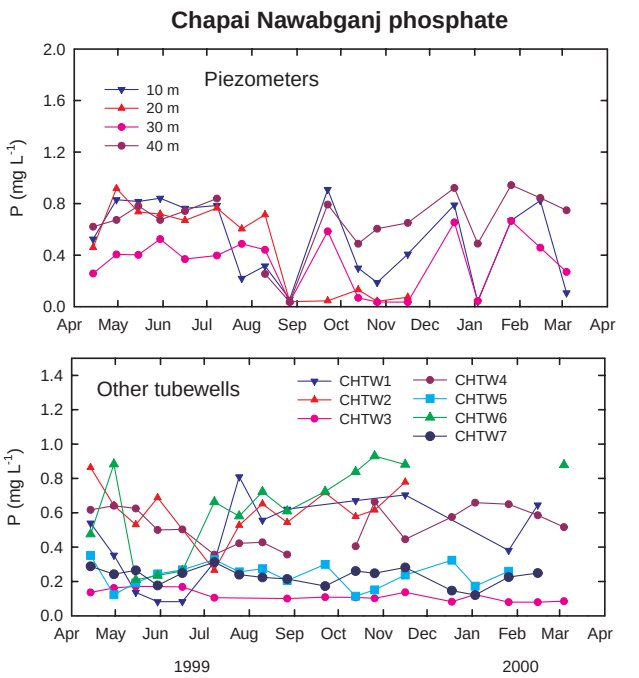

Figure 10.16. Temporal variation in P at the Chapai Nawabganj monitoring sites.

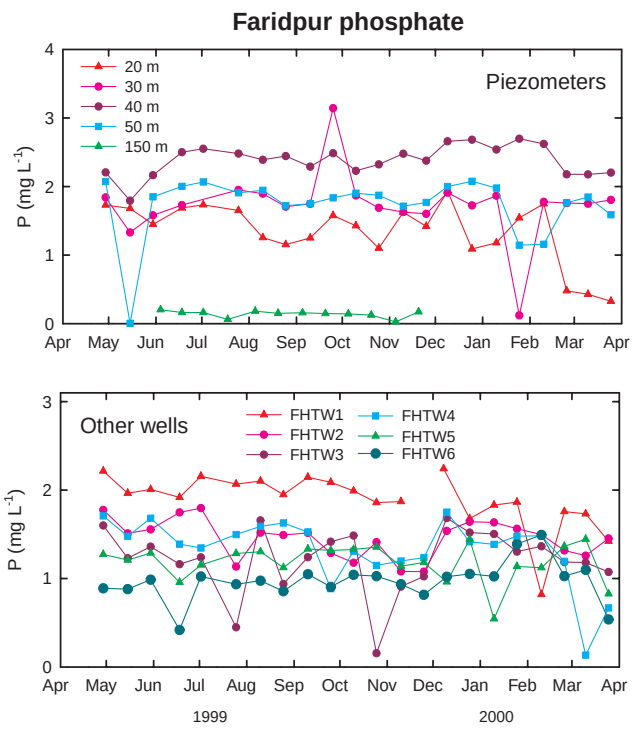

Figure 10.17. Temporal variation in phosphate-P at the Faridpur monitoring sites.

10.18), as reported in Chapter 7. Of these, the lowest and least variable concentrations are found in the 10 m piezometer. Highest concentrations overall are found in the groundwaters from 30–40 m depth. Groundwater from the 50 m poor-yielding piezometer shows the greatest variability with a maximum in July–August 1999. It is not clear how much of the initial variability in the P concentrations

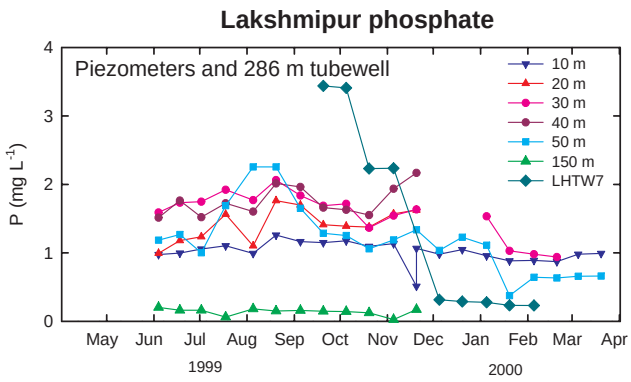

Figure 10.18. Temporal variation in phosphate-P at the Lakshmipur monitoring site.

in the piezometers is related to disturbance of the groundwater due to drilling.

The deep (150 m) piezometer has much lower P concentrations (typically <0.2 mg L^{-1}) and over the period where data are available showed little variation. Concentrations in the deeper (286 m) LHTW7 tubewell were also low in the period December 1999 to February 2000, but for reasons which are unclear, had dropped sharply in the 3-month interval previously, from an initial high of 3.3 mg L^{-1} (Figure 10.18). Continued monitoring would help to identify the causes, repeatability and significance of this trend.

10.8 Conclusions

- Groundwaters have been monitored over a period of up to 12 months in specially-drilled piezometers and a selection of existing tubewells and dug wells in the Special Study Areas.
- The tubewells were pumped before sampling but piezometers are not pumped between sample periods and the other tubewells are equipped with hand pumps for normal domestic use. The temporal variations in water level and chemistry therefore reflect changes in the aquifers without heavy pumping. Nonetheless, the conditions are representative of the real situation where most groundwater abstraction is from hand pumps.
- Water levels show varying responses to seasonal monsoon rainfall. The greatest variation and deepest levels are seen at Chapai Nawabganj and the least at Lakshmipur. Hydrographs of the shallow piezometers are similar at each location and suggest that good hydraulic connections exist within the shallow aquifer.
- At Faridpur, the hydrograph of the 150 m piezometer is similar to those at shallow depths, suggesting some hydraulic connection. Despite this, chemical compositions are very different in the two depth ranges.
- At Lakshmipur, the 150 m piezometer has a distinctive hydrograph with a much smaller seasonal variation, suggesting hydraulic separation between the shallow (≤ 50 m) and deep aquifers.

- Arsenic concentrations show little notable temporal variation in most of the monitored wells. Two shallow piezometers from Lakshmipur showed possible small trends, but while one increased, the other decreased and there was no consistent pattern among the piezometers. Concentrations of As were consistently lowest in the 10 m piezometers (Chapai Nawabganj, Lakshmipur), the dug wells (Chapai Nawabganj) and the deep tubewells (Faridpur and Lakshmipur). At Faridpur, concentrations decreased systematically with depth over the depth range 20–50 m.
- Sodium and Cl are indicators of the temporal and spatial variations in groundwater salinity. Concentrations are low in shallow tubewells from Faridpur and Chapai Nawabganj but much higher in the dug wells from Chapai Nawabganj as a result of evaporation and/or pollution, and the Lakshmipur tubewells as a result of a seawater component in the aquifer. Groundwater is notably fresh in the 286 m tubewell from Lakshmipur. Concentrations of Na and Cl often decreased during the monsoon period perhaps as a result of dilution by recharge. This effect was greatest at the shallowest depths.
- Sulphate concentrations, as reported elsewhere (Chapters 6, 7) were generally low. At shallow depths where concentrations were greatest, they also tended to decrease during the monsoon period. Concentrations increased with depth in the Lakshmipur piezometers as a result of increased salinity, but nonetheless showed evidence of significant loss (compared to Cl and Na concentrations) as a result of sulphate reduction.
- Concentrations of P were variable but often high (often > 1 mg L^{-1}). There was little consistent trend in absolute concentrations with depth. Trends showed some similarities, but also some differences, with those for As at each site.
- The monitoring period gives some preliminary information about temporal trends in water quality over a range of depths in the aquifers, but continued monitoring for a period of several more years is required to test the consistency of observed seasonal variations and record potential trends over longer timescales.
- The sampling interval used in this study reveals variations over periods of weeks, to months, to seasons but does not give any information over shorter timescales (hours or days). Some systematic monitoring at these timescales is required to explore this.
- We caution against reaching hasty conclusions about the expected long-term trends in water quality especially where substantial flow has been induced by pumping.