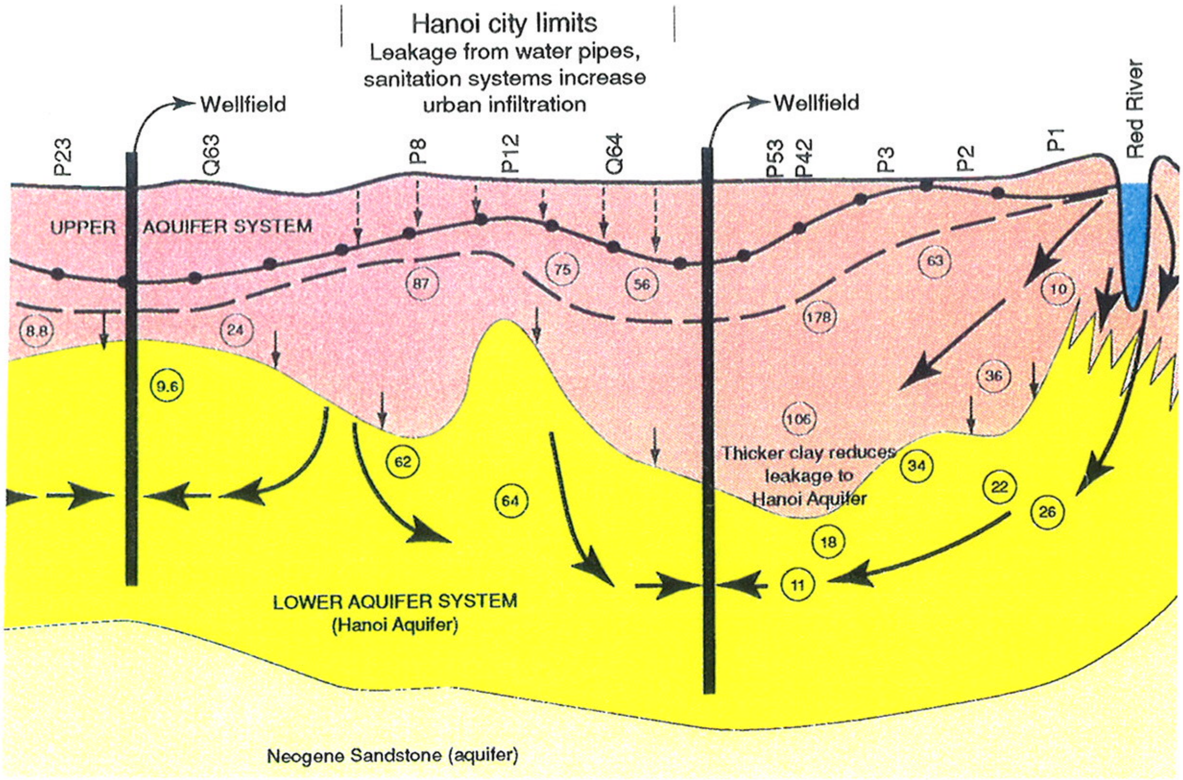
British Geological Survey

TECHNICAL REPORT WC/96/22
Overseas Geology Series

THE EFFECT OF URBANISATION ON THE GROUNDWATER QUALITY BENEATH THE CITY OF HANOI, VIETNAM

A joint project between the British Geological Survey (BGS) and the Geological Survey of Vietnam (GSV)

J M Trafford, A R Lawrence, D M J Macdonald, Nguyen Van Dan, Dang Ngoc Tran and Nguyen Thi Ha



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Sigatoka River flood plain, Fiji

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PREFACE

This report describes a special study carried out as part of a project entitled 'Groundwater development in alluvial aquifers', Project R5561 (93/2), under the Overseas Development Administration (ODA) Technology Development and Research (TDR) programme of technical assistance to developing countries. The impact of urbanisation on alluvial aquifers is a worldwide problem. The water balance and water quality of the alluviums can be affected and degradation of the resource can occur. This report is one case history of such an occurrence.

EXECUTIVE SUMMARY

Groundwater is the source for urban water supply for the city of Hanoi. This water is obtained from well fields, both within and immediately outside of the urban area, which pump from the semi-confined 'Hanoi' aquifer.

As a consequence of the increase in population and the improved urban water supply coverage, groundwater abstraction has increased considerably since the 1950s and 1960s and this has resulted in a depression of the water levels around the main well fields.

The depression of the water levels in the Hanoi aquifer has induced substantial recharge both as leakage through the overlying semiconfining layer and as seepage from the deeply incised Red River channels. Concern has been expressed that this induced recharge may result in a deterioration of groundwater quality since most of the city's urban water (both wastewater and solid waste) are disposed to the ground or to surface water courses through which recharge occurs.

The results of this study are as follow:- (i) all the groundwater beneath Hanoi has been replaced by modern (post 1950s) recharge, (ii) some slight increase in chloride and bicarbonate has been observed in both the shallow and deeper aquifers beneath the city and are believed to be associated with urban waste disposal, (iii) significant concentrations of ammonia are observed in both the shallow and deep aquifer, especially to the south of the city. The cause of the ammonia is unclear, although a natural source is possible, (iv) the good quality of the groundwater in the Hanoi aquifer is maintained because of high natural infiltration rates and substantial recharge from the Red River.

Groundwater quality is considered unlikely to deteriorate substantially in the near future. However, whilst the outlook is positive it is important to (a) continue monitoring to provide early warning of any changes to the groundwater system and (b) give consideration to the local geology/hydrogeology when implementing development plans (for example the design/location of landfills).

The work described in this report was carried out as a special study under the project 'Groundwater development in alluvial aquifers'. The project was funded by the United Kingdom Overseas Development Administration under its Technology Development and Research programme (Project R5561).

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1. INTRODUCTION

This report details work carried out in Hanoi, Vietnam from August 1994 to August 1995 and forms part of an Overseas Development Administration (ODA) funded, Technology Development and Research (TDR) project studying various aspects of unconsolidated sedimentary aquifers. The project was carried out in collaboration with the Hydrogeological Division No:2 of the Geological Survey of Vietnam (GSV).

The objectives of this sub-project were to (i) characterise the baseline chemistry with respect to inorganic chemical and isotopic analysis, (ii) assess the risk to groundwater quality posed by urbanisation and (iii) predict any long-term trends.

Before 1954 groundwater from deeper aquifers was supplied to relatively few people in Hanoi; most of the local people used surface water or shallow dug wells. Since independence, abstraction has increased rapidly (see Figure 1) from 141,000 m^3/d in the 1960s to 164,000 m^3/d in the 1970s and to present day rates of 410,000 m^3/d. The projected abstraction rate by 2010 is 685,000 m^3/d. Given the importance of groundwater for the city, concern has been expressed about possible degradation of this resource as a result of deterioration in quality. The main concerns are pollution caused by:

i) On-site sanitation systems.
ii) Domestic and industrial wastes discharged to surface water courses.
iii) Disposal of solid wastes to landfill sites.

2. REGIONAL SETTING

The city of Hanoi, the capital of the Socialist Republic of Vietnam, is situated in the north-east of the country and lies close to the Red River near the centre of the Bacbo Plain. The resident population of the city is about 3 million whilst another 1 million people commuting into the city every day. The capital is an important industrial centre for the country.

Hanoi is underlain by 50-90 m of unconsolidated sediments of alluvial and marine origin. These sediments contain large volumes of water and aquifers within these deposits are used for the city's water-supply. The main source of groundwater is the Hanoi aquifer. This aquifer is semi-confined and is overlain by at least 20-40 m of semi-permeable sands, silts and clays. The majority of the population have access to treated water supplied by 9 large well fields in and around the city. The volume of groundwater currently pumped is 410,000 m^3/d of which 80% is for public supply and the balance, abstracted by private boreholes, is mainly for industrial use. Recently, as a result of the improved public supply system, the private groundwater abstraction for industry has reduced by 20-30%. Despite the large volumes of water available in the Red River, groundwater is preferred because of the high cost of treating the turbid river water.

The city is unsewered, with liquid waste being disposed of via open drains running along the edge of the roads to man made drainage canals or tributaries of the Red River. The To Lich and Lu Rivers are the main waste water courses in the urban area. Solid waste is swept into the streets every evening and collected by lorries which transport it to one of the landfill sites in the area. These sites are unlined and rely on the underlying clay layers to prevent seepage to the aquifer. A landfill site located on the eastern bank of the Red River has recently been abandoned because of evidence of groundwater contamination.

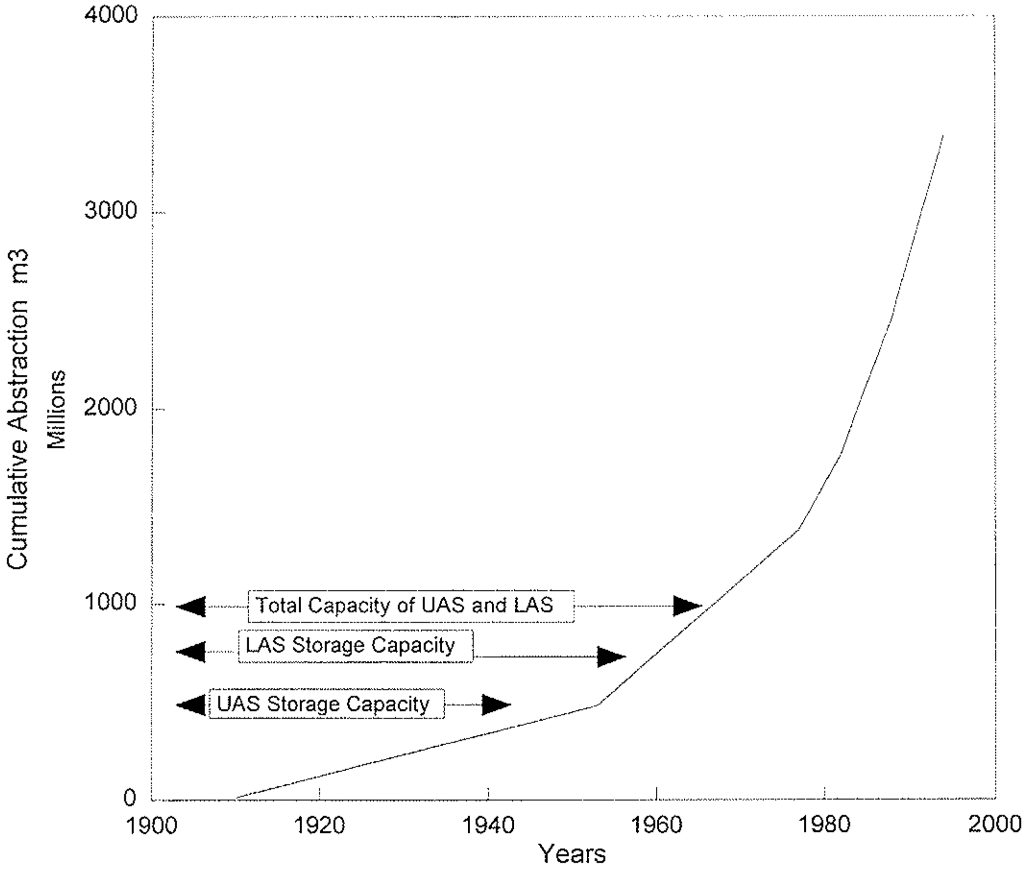


Figure 1: Cumulative abstraction for Hanoi city 1910-1994

The climate is characterised by two distinct seasons; a rainy hot season (May-October) and a dry-cool season (November-April). Mean annual temperatures in the rainy season are 29°C and in the cool season, 16°C. Rainfall amounts vary, but the long term average is nearly 1700 mm (1983-1990). On average, 80-90% of the annual rainfall occurs within the rainy season.

The long term average evaporation rate is 1025 mm; recharge from rainfall is restricted to the rainy season, during the dry season evaporation exceeds rainfall and consequently no infiltration from rainfall to groundwater occurs.

The Red River is the most important river of the northern part of Vietnam and drains large areas of Yunnan province, SW China. Its river channel, near Hanoi, is deeply incised and in places has cut down to expose the underlying semi-confined Hanoi aquifer.

Flow in the Red River is also greatly affected by seasonal changes, it's average level in the wet season is about 10 metres and in the dry season is about 2 metres above sea level.

3. GEOLOGY AND HYDROGEOLOGICAL UNITS

3.1 Description and Classification of Deposits

The Bacbo Plain is a large, flat sedimentary basin consisting of Quaternary sediments of alluvial and marine origin resting on Tertiary deposits of Neogene age. The area of the basin is some 11000 km^2 (Figure 2).

The Quaternary and upper Neogene deposits consist of sands, gravels and cobbles interbedded with finer layers of clay, silt and sand. The total thickness of the deposits exceeds 400 m whilst individual sand and gravel layers can exceed 30 m; the sand and gravel beds are usually channel deposits and are lenticular in form. In addition, climatic changes, with associated sea level oscillations, have produced rapid lithological changes within a vertical sequence. As a consequence the geology is complex with considerable variation in lithology, both laterally and vertically, within short distances. A more detailed description of the geology is described in NguyenVan Dan and Tran Minh (1992) and Mathers *et al* (1996).

The layers within the unconsolidated strata have been classified into different hydrogeological units (Table 1). In this report the aquifer system for the Quaternary deposits has been simplified to an upper and lower aquifer system. The Upper Aquifer System (UAS) comprises one or two minor aquifers separated by less permeable clayey layers or aquitards. The UAS is exploited for water to only a limited extent, mainly by shallow dugwells for domestic supply and irrigation. The importance of the UAS is not due to the quantities of water abstracted from it but because it is through this layer that most of the recharge to the Lower Aquifer System (LAS), the main source of water for Hanoi, occurs.

3.1.1 *The Upper Aquifer System (UAS)*

The UAS typically comprises up to 70 m of sands, silts and clays although 20-40 m is more common. Two permeable layers (minor aquifers) have been recognised within the UAS; a shallow Holocene aquifer which is essentially unconfined and a deeper semi-confined aquifer of Pleistocene age. There is considerable variation in the thickness of these layers due to the meandering of the river channel and changes in river levels; at some localities only one aquifer is present. A geological cross-section beneath Hanoi shows the variation in thickness of the UAS (Figure 3).

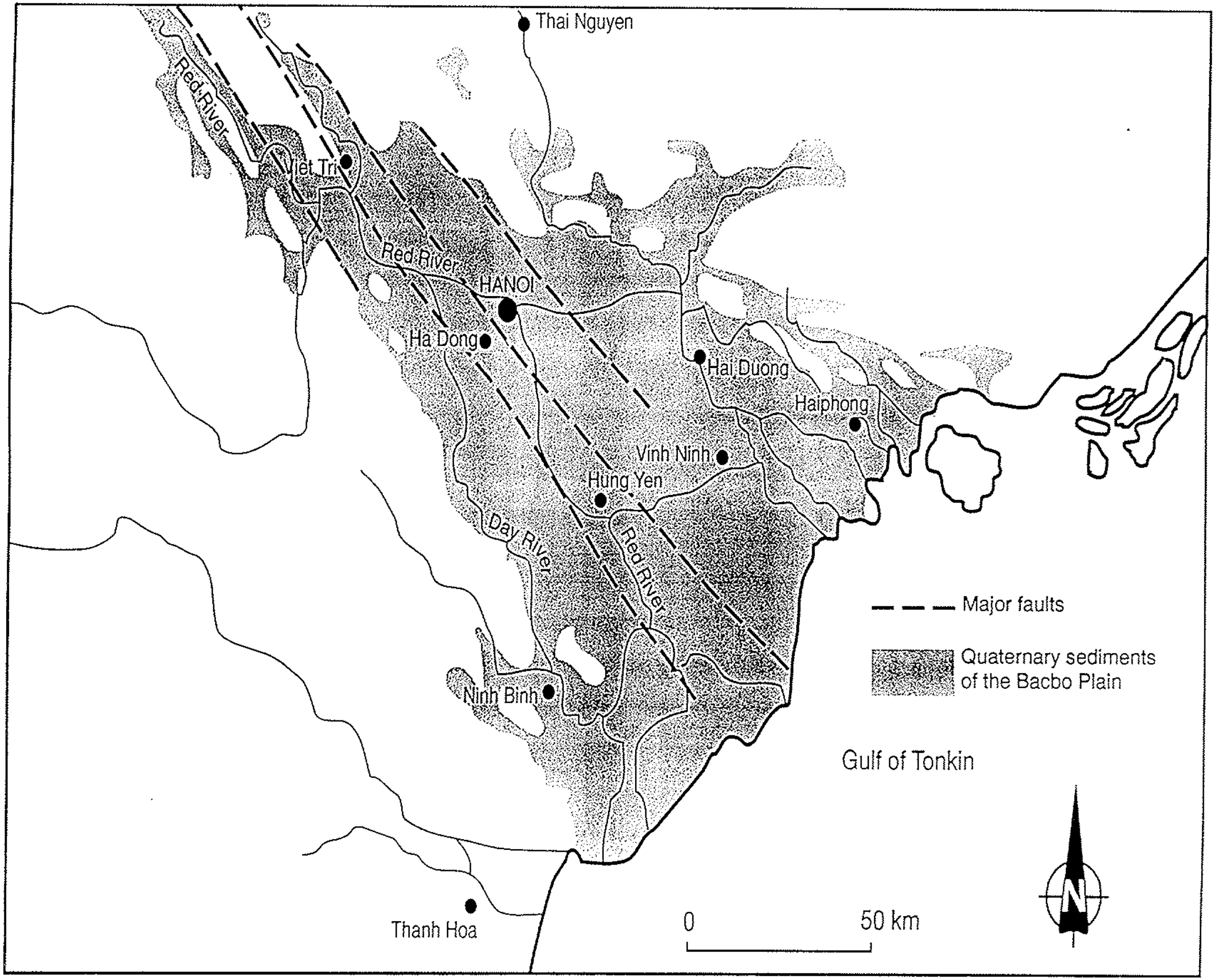


Figure 2 Location map of Hanoi showing the extent of the Bacbo Plain

SYSTEM	DIVISION	FORMATION	THICKNESS (m)	LITHOLOGY	UAS/LAS*	HYDROGEOLOGICAL SIGNIFICANCE
QUATERNARY	HOLOCENE	THAI BINH	11-46	Recent alluvial sediment (sand, clay sand, sandy clay)	UAS	Unconfined Aquifer
		HAI HUNG	5-17	Lacustrine sediment (clay)	UAS	Aquitard not always present
	PLEISTOCENE	VINH PHUC	5-18	Lacustrine sediments (clay, sandy clay).	UAS	Aquitard not always present
			43	Lacustrine sediments (sand and gravel)	UAS	Confined/Semiconfined Aquifer
		HA NOI	21	Alluvial deposits (clay)	LAS	Aquitard
			37	Alluvial deposits (sand, gravel, cobbles, pebbles)	LAS	Mainly confined Aquifer
		LE CHI	28	Alluvial deposits (sand, gravel, cobbles, pebbles	LAS	Mainly confined Aquifer
TERTIARY	PLIOCENE	VIN BAO	150	Estuarine to shallow marine formation (cobbles and pebbles, sandstone, siltstone, shale)		Aquifer

* UAS = Upper Aquifer System
LAS = Lower Aquifer System

Table 1: Description and classification of deposits underlying Hanoi

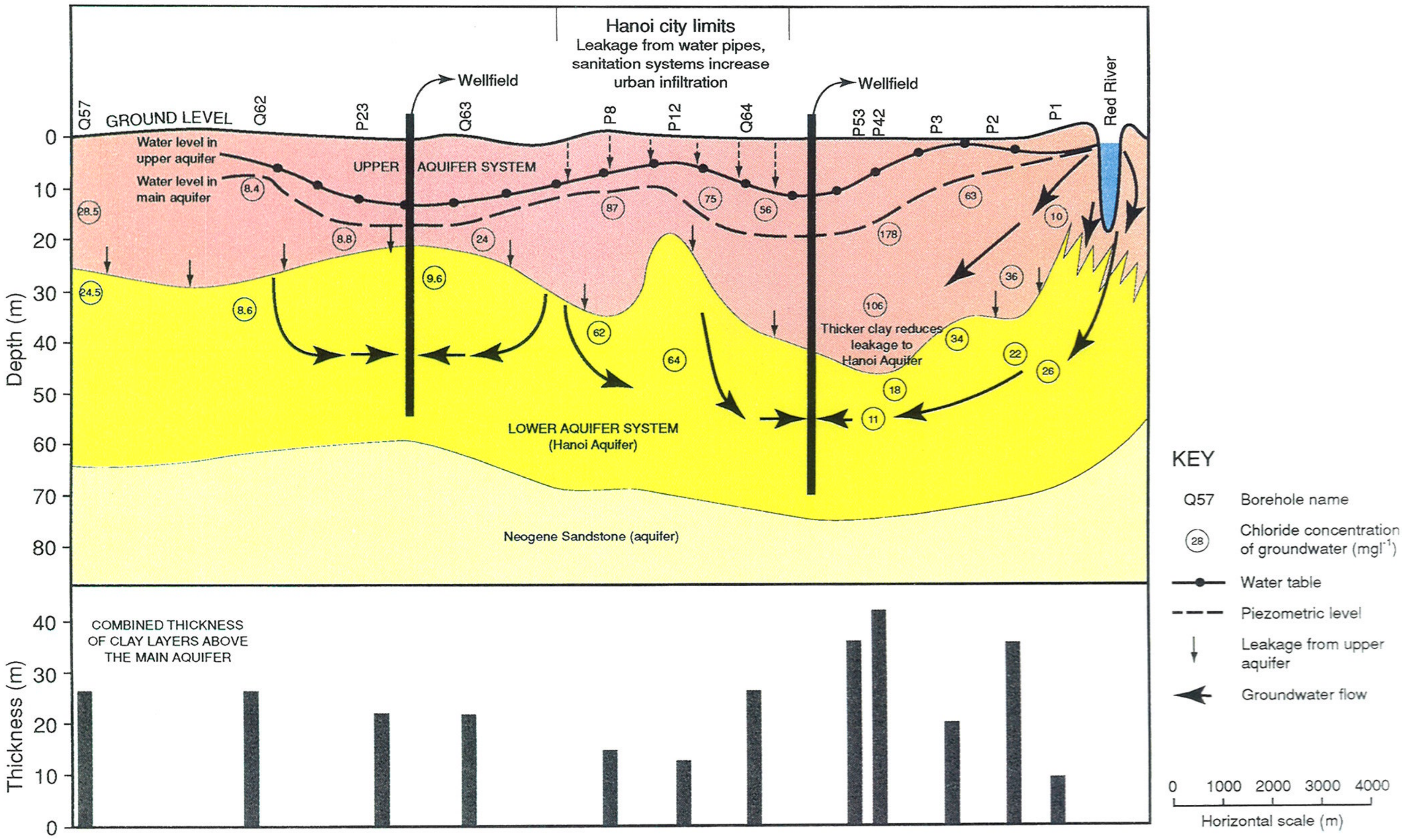


Figure 3 Geological cross-section beneath Hanoi showing the variation in thickness of the UAS and the extent of the clay layers above the LAS

The UAS acts as a semi-confining or 'leaky' layer to the underlying Hanoi aquifer or the LAS. The degree of hydraulic continuity between the upper and lower aquifer systems depends on the lithology. Given the variability in the lithology of the strata and the lateral discontinuity of individual layers, the amount of water that can leak through the UAS is also highly variable. In the Yen Phu area, close to the Red River in the north east of the city, the three aquifer units are almost in total continuity, (no intermediate clay layers), forming a permeable 'window' to the underlying layers. In this area the potential for rapid recharge to the Hanoi aquifer is likely to be greater.

Likewise the transmissivity is variable; for the Holocene aquifer, transmissivity as determined by pumping test varies from 50-700 m^2/d (Tran Minh and Nguyen Van Dan, 1991). The specific yield of the UAS is of the order 0.05-0.25.

3.1.2 *The Lower Aquifer System (LAS)*

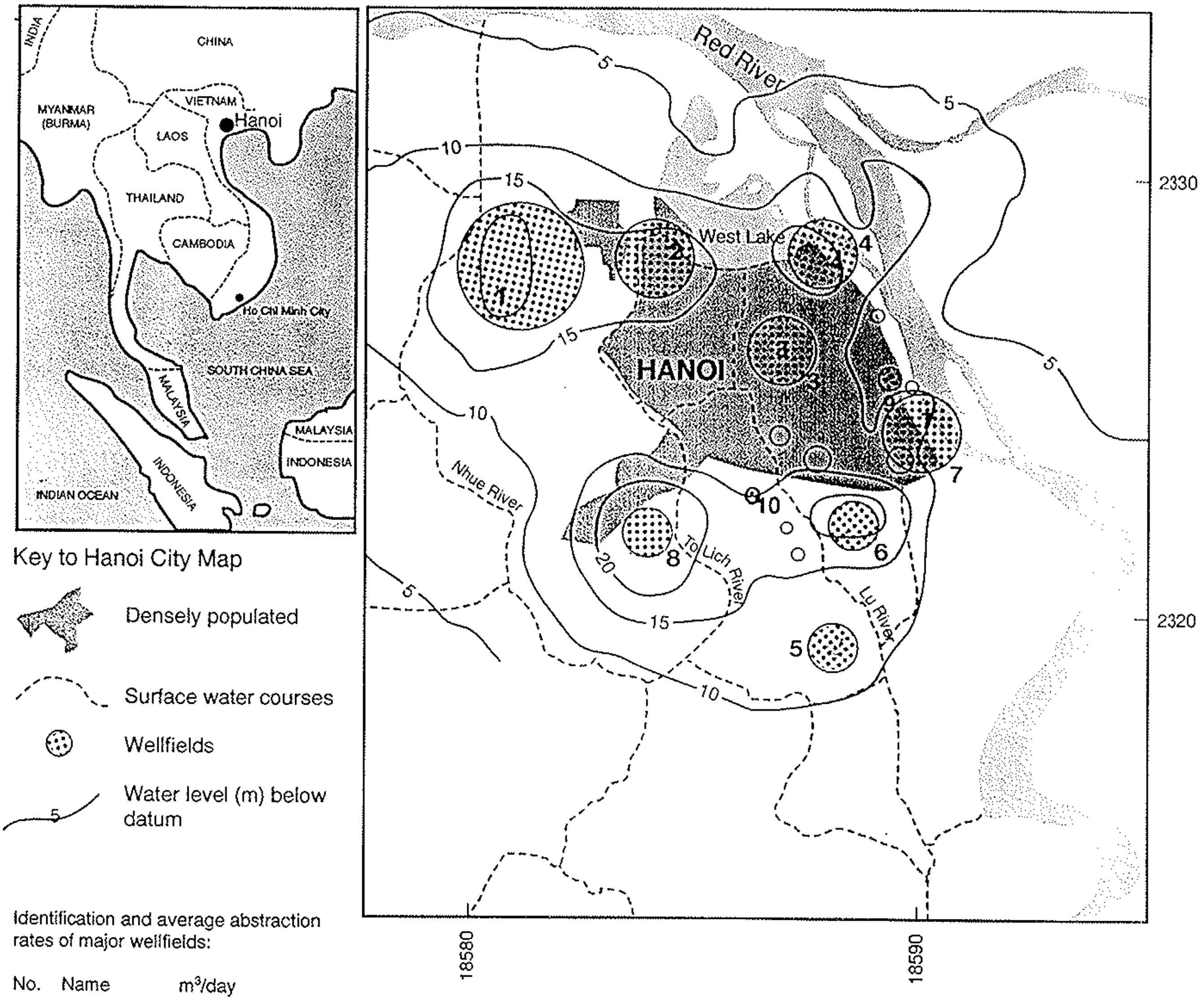
The Lower Aquifer System is defined here as the Hanoi aquifer of Lower-Middle Pleistocene age. This is the main water supply aquifer for the city of Hanoi and is a highly permeable sand and gravel aquifer. Results of pumping tests performed on this aquifer indicate transmissivities in the range 700-2300 m^2/d and a storage coefficient between .002-0.1 (Tran Minh and Nguyen Van Dan, 1991). The storage coefficient clearly indicates the aquifer, at least in some areas, is semi-confined (Tran Minh and Nguyen Van Dan, 1991).

Prior to independence in 1954, groundwater development of this aquifer was limited. The bulk of the population obtained their water supply from either shallow wells or from surface water sources. Since the 1960s, groundwater development for the city has increased with 9 major and 12 minor well-fields currently pumping 330,000 m^3/day to the city's water supply. In addition more than 80,000 m^3/day is pumped from private boreholes used mostly for industrial water supply.

In response to this pumping, groundwater levels (piezometric levels) in the LAS have declined. The cones of depression produced are, not surprisingly, greatest around and close to Hanoi where the well-fields are located (Figure 4). Water levels in the UAS have also declined but less than in the LAS and a significant head difference between these two aquifer systems now exists (Figure 5).

The LAS receives substantial recharge from the Red River (and other surface water courses) especially where the semiconfining layer is either thin and/or relatively permeable or absent altogether. Evidence of leakage from the To Lich river and from the Trucbach, West and Quangba Lakes has been seen in some areas (Tran Minh and Nguyen Van Dan, 1991).

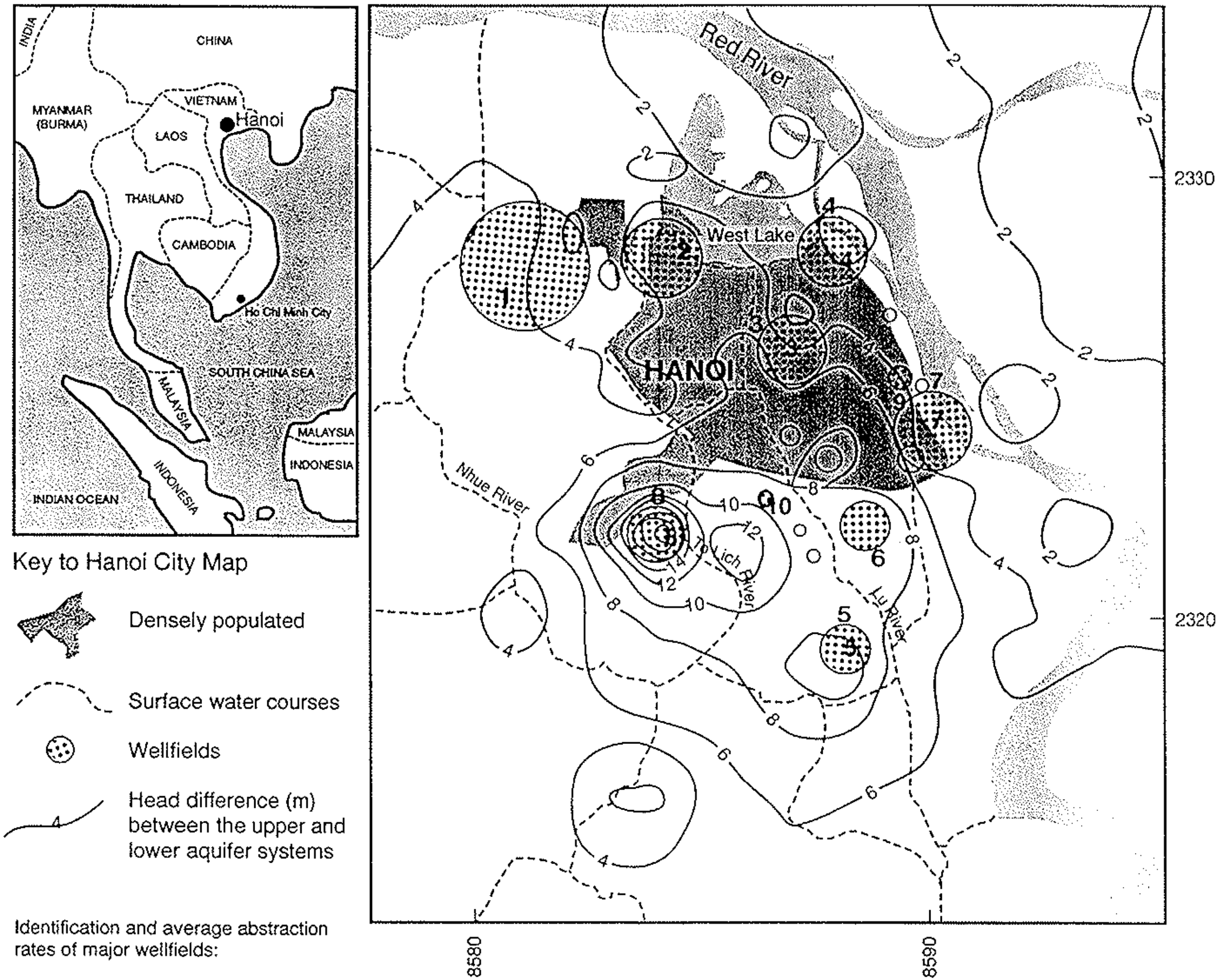
`The Hanoi aquifer is underlain by a sand of Neogene age, (unconsolidated at its junction). Its piezometric level, when not influenced by pumping is between 1 and 3.5 metres below ground level. The Neogene sands although much less permeable than the overlying strata can be considered to be water-bearing in some areas, particularly in the central and southeastern region of the city and is likely to be in hydraulic continuity with the Hanoi aquifer. The water pumped from the Neogene sand is mostly fresh, but at some localities brackish water occurs which could adversely affect water quality in the Hanoi aquifer.



Identification and average abstraction rates of major wellfields:

No.	Name	m^3/day
1	Mai Dich	54900
2	Ngoc Ha	47160
3	Ngo Si Lien	45280
4	Yen Phu	43870
5	Phap Van	30000
6	Tuong Mai	28800
7	Luong Yen	27020
8	Ha Dinh	26920
9	Don Thuy	9730
10	Bach Mai	3500

Figure 4 Water levels in the LAS showing cones of depression as a result of pumping



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7	Luong Yen	27020
8	Ha Dinh	26920
9	Don Thuy	9730
10	Bach Mai	3500

Figure 5 Water level difference between the UAS and LAS

3.2 Evolution of Groundwater System

Prior to the development of the Hanoi aquifer and the abstraction of large volumes of groundwater in the second half of the 20th century, the aquifer system must have been largely static. The flat, low-lying and extensive plain precludes the existence of steep, natural groundwater gradients, hence groundwater velocities in the LAS would have been low, probably in the range 10-100 m/a. Flushing of the aquifer by recent recharge would have been limited and groundwater in the Hanoi aquifer may have been several hundred years old.

Originally vertical groundwater gradients are likely to have been upwards (but low) within the centre and lower reaches of the plain . Active groundwater circulation being mainly restricted to the shallow layers in response to abstraction from shallow wells and to discharge to and recharge from rivers (Figure 6a). However, as the Red River also penetrates the LAS, recharge of this aquifer via the river would occur.

Following the drilling of boreholes to the LAS and the large scale abstraction from the Hanoi aquifer in the 1960s and 1970s, vertical groundwater gradients would have been reversed and leakage from the UAS to LAS induced (Figure 6b). The evolution of the flow system and reversal of vertical gradients is similar to that described for the city of Hat Yai in Thailand (Lawrence *et al*, 1994). This conceptual model suggests that some of the groundwater initially pumped from the Hanoi aquifer would have been relatively old water. Given the large volumes of groundwater pumped from the deeper aquifers (Figure 1) a front of modern recharge will have migrated downwards through the UAS in response to this abstraction. The quality of this modern recharge and its rate of movement downwards are critical factors in any assessment of the long term impact on groundwater quality in the Hanoi aquifer.

The approximate storage capacity of the two aquifer systems has been calculated to be 315 million m^3 for the top aquifer and 630 million m^3 for the main aquifer (assuming that the top aquifer has a porosity of 5%; the lower aquifer has a porosity of 10%; that both are each about 30 metres in depth and the area of urban pumping is 210 km^2). The total abstraction over the last 84 years has been about 3.5 billion m^3 and it is clear, therefore, that the bulk of the water pumped today will be recently recharged. With such considerable volumes of groundwater pumped, over a relatively small area, rates of downward leakage are likely to be high (~1-5 m/a).

3.3 Sources of Recharge

Recharge in the early part of the 20th century would have occurred mainly in response to the rise of the river level, both for the UAS and the LAS, however as a result of urbanisation, increased abstraction rates and the subsequent lowering of water levels, new sources of recharge were created.

The sources of recharge and their relative importance and quality are listed in Table 2. The potential for recharge is considerable given the relatively high rainfall and the large volumes of surface water. Recharge is likely to be limited more by the rate at which infiltration can occur and the thickness of the unsaturated zone, than by the availability of potential recharge. Infiltration will be greatest where the subsurface layers are more permeable and where the water table is relatively deep. The latter condition exists around the major wellfields where a significant lowering of the water table in response to induced leakage to the deeper aquifer occurs.

Whilst impermeablisation of the catchment within the urban area is likely to reduce direct infiltration from rainfall, this is likely to be more than offset by increased recharge from leaking water mains and on site sanitation systems. For most cities especially those that are either unsewered or only partly sewered, urban recharge is normally significantly higher than the pre-urban or 'natural' rate (Foster *et al*, 1994).

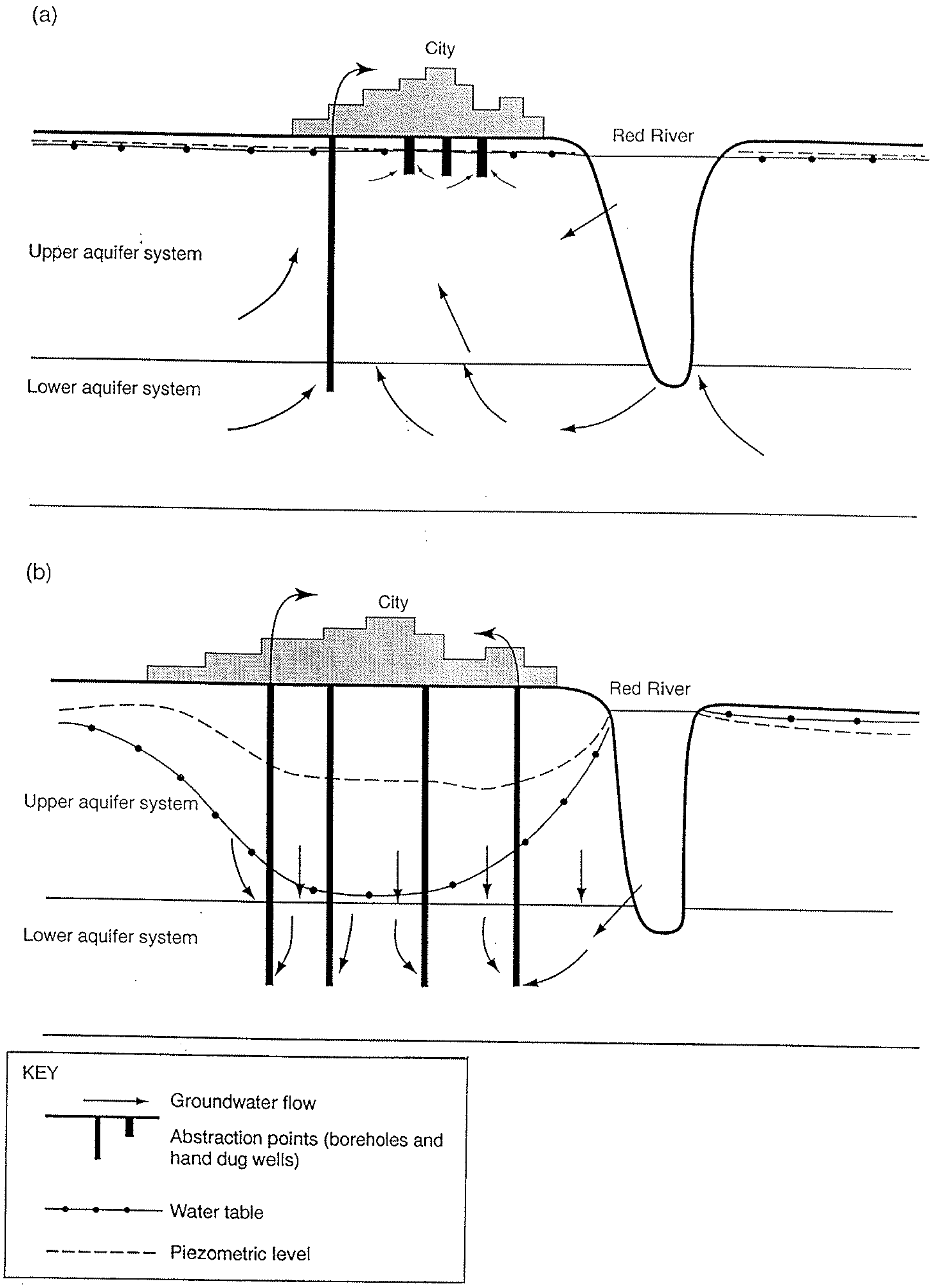

Figure 6 a-b Schematic diagram of the groundwater flow system pre 1950 (a) and the present day (b)

Source of recharge	Area	Importance Non-urban	 Urban	Comment	Quality
Rainfall	widespread	major	major	Urbanisation reduces infiltration	Good
Irrigation	widespread outside city	major	minor (negligible)	Irrigation in urban areas restricted to parks and gardens.	Generally good. May have elevated N or Cl.
Seepage from surface water	local or linear	probably major	major	Seepage induced where pumping lowers waterlevels and subsurface is relatively permeable. Significant volume of wastewater discharged to surface water courses	Generally good except where wastewater in surface water
Leaking water mains	widespread in city	negligible	major	Estimated to be 65% in Hanoi.	Good
Soakaway drainage	widespread in city	minor	moderate	Where no mains drainage exists, disposal of sullage waters via soakaways would increase the importance of this recharge source.	Poor
Disposal of domestic sullage waters	widespread in city	minor	major	The disposal of sullage waters is usually either to surface water courses (via drains) or to ground via soakaways.	Poor
Run-off from paved areas	widespread in city	minor	minor - moderate	Importance depends on drainage arrangement and whether it's directed to subsurface soakaways or to surface water courses.	Good to poor

Table 2 Sources of recharge and their relative importance to groundwater quality

4. SAMPLING AND ANALYTICAL METHODS

4.1 Sampling Strategy

The work programme for sampling was initiated in June 1994 following a visit by British Geological Survey (BGS) staff to train counterpart staff, from the Hydrogeological Division No:2, in field analysis and sampling techniques.

For the urbanisation study, an area of some 150 km^2 bounded by the Nhue River in the west and the Red River in the east was designated (see Figure 7). The majority of boreholes sampled were either observation holes (part of the Hanoi Monitoring network) or public supply boreholes. All of the public supply wells pump from the main aquifer, but many of the sites for the Hanoi monitoring network have multiple boreholes within only a few metres of each other, penetrating each aquifer system. Samples taken from the UAS reflect the most recent effects of urban recharge; those from the LAS provide insight into the extent of migration of the plume of recent recharge. Surface waters were also collected from waste water canals, lakes and rivers, as these are potential recharge sources. Site locations were chosen to provide an even distribution of all water types across the area (see Figures 7 and 8) in order that a general overview of the groundwater quality could be obtained.

In an attempt to characterise the baseline hydrochemistry, samples were collected to fall on two cross-sections extending to a maximum of 35 km from Hanoi city (see Figure 9). The sites were mainly used either for domestic supply or irrigation, although some observation boreholes for the Bacbo Plain monitoring project were also used. Outside the city the choice of sites for sampling was very limited, all were located in close proximity to either extensively cultivated land or villages and small towns and it is likely therefore that they are influenced by anthropogenic factors.

The groundwater samples collected and on-site measurements carried out, represented as closely as possible the in-situ conditions of the aquifer. Where a borehole was not regularly pumped, it was flushed to waste for at least 30 minute so as to purge any stagnant water before sampling commenced, (a portable electric submersible pump was used where there was no permanent pumping mechanism). All sampling was carried out as close as practicable to the headworks and prior to any treatment. Where possible pH, Eh, temperature and dissolved oxygen (DO_2) were determined using an in-line anaerobic cell. Alkalinity and conductivity were also measured on-site.

A total of 98 boreholes were sampled during the period from June 1994 until March 1995; of these 28 sites sampled the upper aquifer (UAS) and 60 the main Hanoi aquifer (LAS). Ten surface water samples within the urban area were also collected. The majority of samples from the urban study area were analysed at the Vietnamese Geological Survey laboratories; the baseline samples were returned to the laboratory at Wallingford for analysis.

4.2 Sample Type and Analytical Methodology

During the two visits by BGS staff in June 1994 and February 1995 duplicate samples for inorganic chemical determinands were collected for interlaboratory comparison of data. For this study two samples were collected for analysis at Wallingford, both were filtered on-site (0.45μm) into plastic acid washed bottles and one was acidified to 1% v/v HNO_3. Acidification of the sample is particularly important where determination of iron is required, but it also acts to stabilise other metals by discouraging precipitation and reducing their adsorption onto the container surfaces. In June the GSV collected a pair of unfiltered samples for their analysis, one in a plastic bottle which remained unacidified and one in a glass bottle which was acidified for iron speciation analysis. For the second interlaboratory sampling the GSV samples were standardised with those of the BGS. The results from this study are described in Section 4.3.

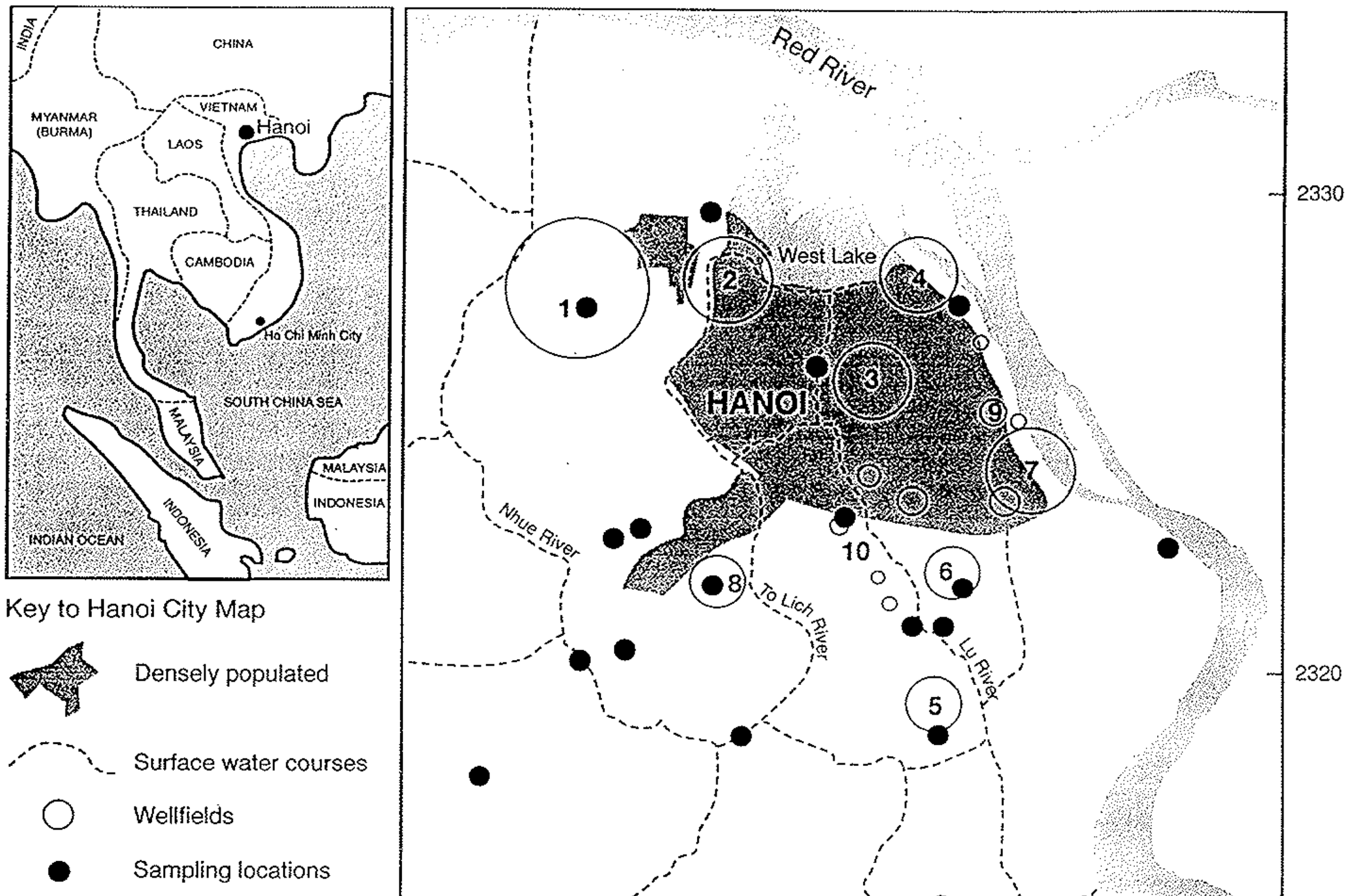

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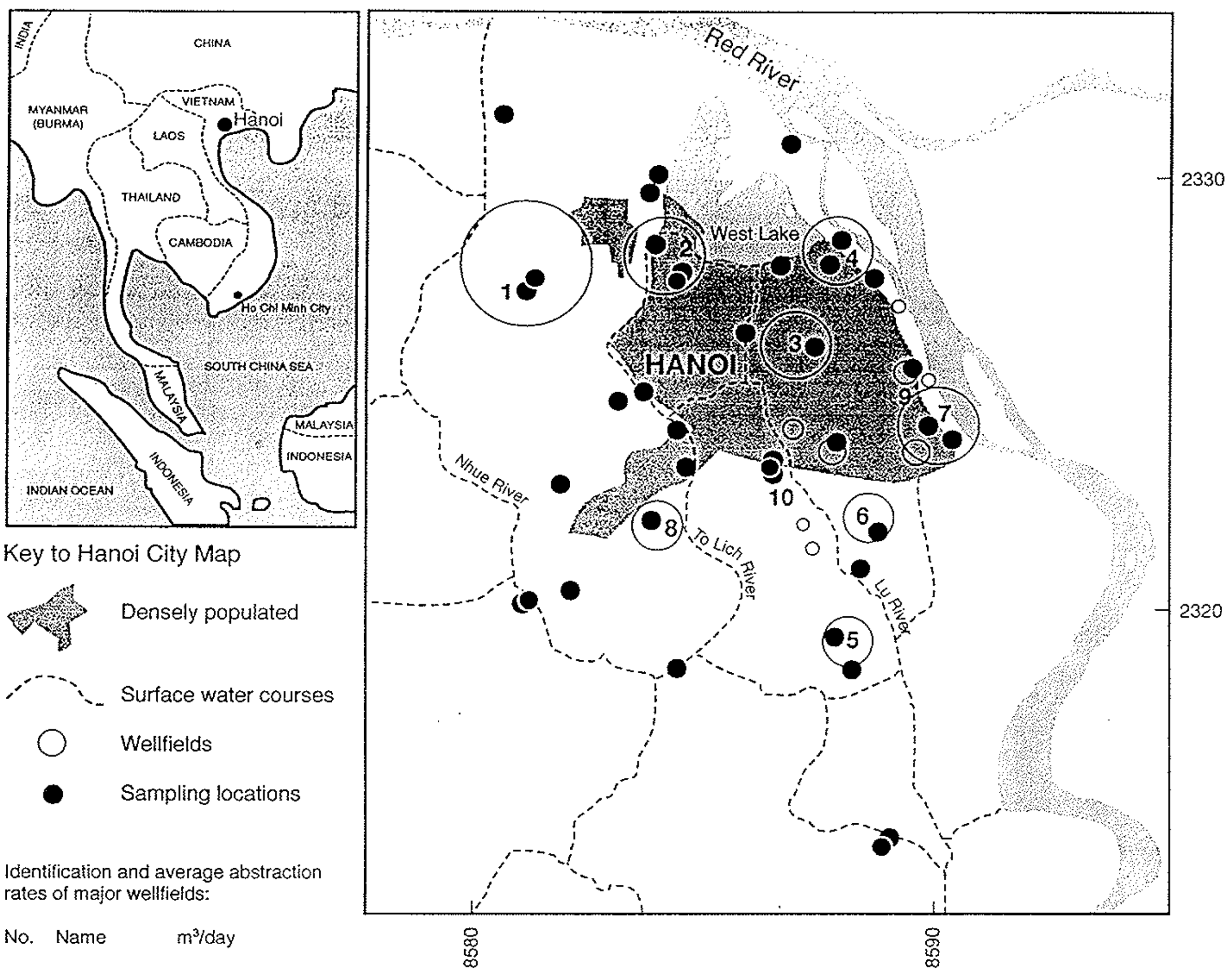
Figure 7 Area of sampling for the urban study and location of sites sampling the UAS



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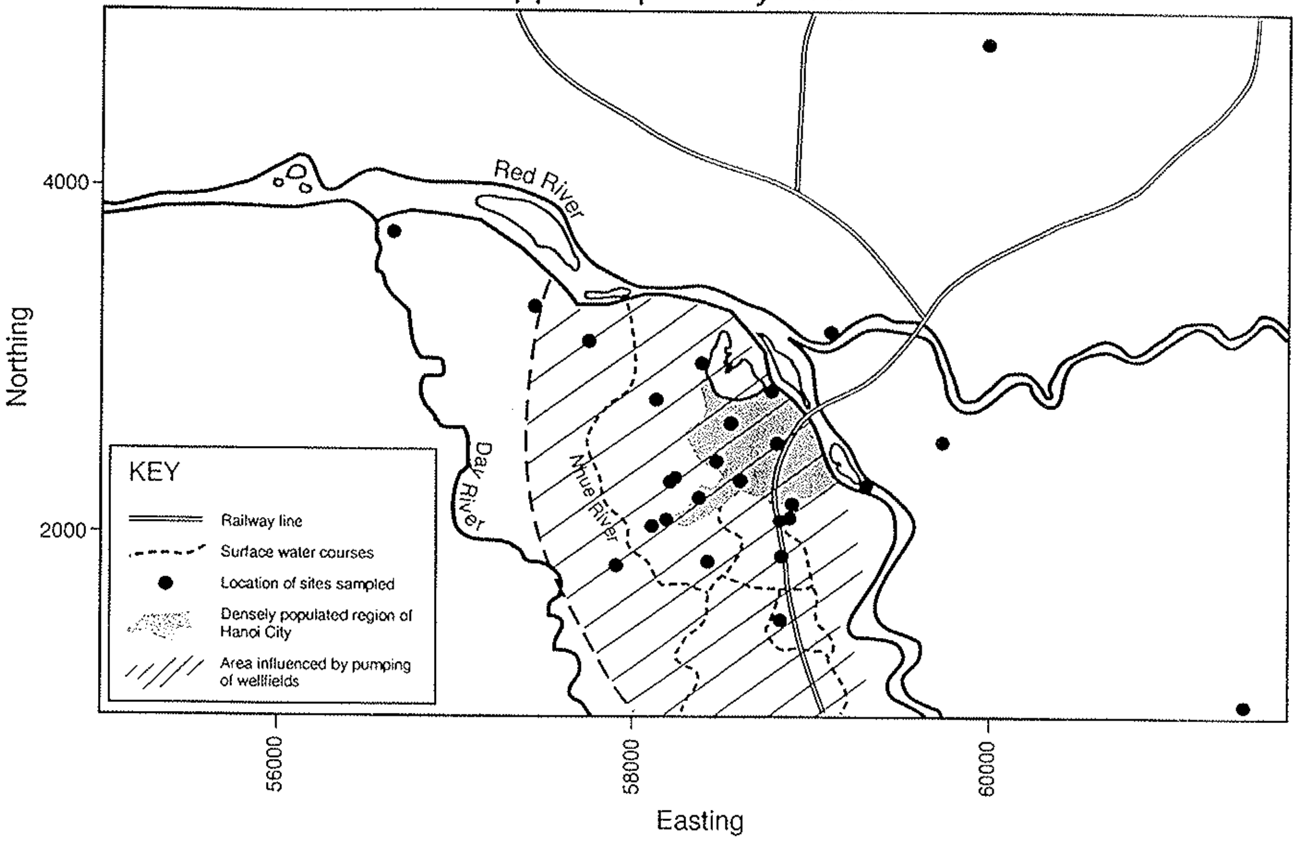
1	Mai Dich	54900
2	Ngoc Ha	47160
3	Ngo Si Lien	45280
4	Yen Phu	43870
5	Phap Van	30000
6	Tuong Mai	28800
7	Luong Yen	27020
8	Ha Dinh	26920
9	Don Thuy	9730
10	Bach Mai	3500

Figure 8 Location of sites for the urban study sampling the LAS

Upper Aquifer System



Lower Aquifer System

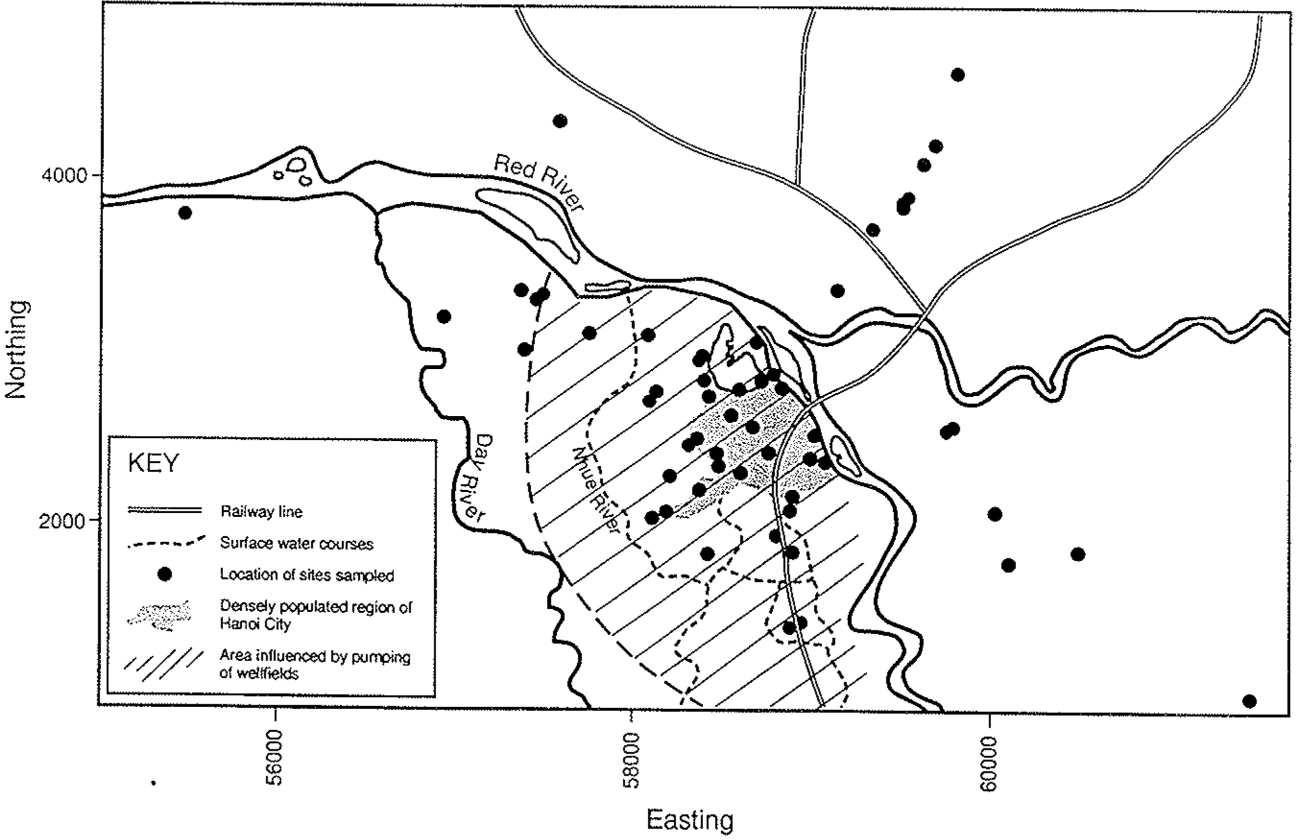


Figure 9 Location map of all boreholes sampled, including those for the baseline study

At selected sites samples were collected for the determination of stable isotopes (δ^2H, $\delta^{18}O$ and $\delta^{13}C_{DIC}$) and total organic carbon (TOC) and returned to the UK for analysis. See Table 3 for further details of sample collection and preservation.

4.2.1 *BGS laboratory*

An ARL 34000C simultaneous inductively coupled plasma optical emission spectrometer (ICP-OES) was used for the analysis of the following: Na, K, Mg, B, Li, SO_4, P_{total}, Si, Sr, Be, Ba, Sc, Y, Mn, Co, Fe_{total}, Zn, Cd, La, Cu, Zr, Cr, Ni, Mo, Al, Pb. Chloride, total oxidised nitrogen (TON, but also interchanged with NO_3 assuming that NO_2 is insignificant), and ammonium were determined on the filtered and unacidified sample by automated colorimetry (using an Auto-Analyser II system) based on classical colorimetric methods. With each batch of samples the accuracy of the analysis was ensured by the inclusion of an independent quality control solution.

A Dionex 2010i ion chromatograph was used to establish the accuracy of the SO_4 data for the first interlaboratory comparison. This also produced duplicate results for Cl, P_{total}, and SO_4, and data for the additional elements of Br, and NO_2.

Stable isotopes were measured by mass spectrometry and TOC was determined by use of a TOCSin II aqueous carbon analyser which comprises of oxidation by combustion followed by a flame ionisation detection step.

4.2.2 *Geological Survey of Vietnam, Hydrogeological Division No: 2 laboratory*

A flame photometer was used for determination of the cations, sodium and potassium, whilst calcium and magnesium were analysed by complexation titrations. The anions SO_4, HCO_3, and Cl were analysed by complexation titration, acid-base titration and titration with $AgNO_3$ respectively. The nitrogen species, ferrous and ferric iron and manganese were analysed using classical colorimetric methods followed by detection using UV-VIS Spectrophotometry.

The unfiltered and unacidified sample was used for the analysis of all determinands except the iron for which the unfiltered acidified sample was used. Whilst it is possible to determine the two species of iron by colorimetric spectrophotometry, it is doubtful that the true speciation of the in-situ groundwater is being measured when both are determined from one unfiltered and acidified solution (see Section 4.3 below).

PARAMETERS FOR ANALYSIS	CONTAINER TYPE	TREATMENT AND PRESERVATION	ANALYTICAL METHOD
δ^2H and δ^{18}O	30ml air tight glass McCartney bottles	Unfiltered and unacidified. Stored at 4°C in the dark	Mass Spectrometry
δ^{13}C	30ml air tight glass McCartney bottles	Coprecipitaion of carbon with barium hydroxide by the addition of sodium hydroxide and then barium chloride to a 250 ml unfiltered sample. Collection of the precipitate into an airtight container.	Mass Spectrometry
TOC	10 ml glass bottle, with caps lined with aluminium foil. (Bottles had been chromic acid washed and thoroughly rinsed with deionised water before use).	Unfiltered and unacidified Plastic gloves worn during sampling to minimise contamination. Stored at 4°C in the dark	TOCSin II aqueous carbon analyser

Table 3 Sampling and analytical methodology for TOC and stable isotopes

4.3 Assessment of Data Quality

4.3.1 *Laboratory analysis*

In June 1994, 21 duplicate samples were collected in order that an interlaboratory comparison of the analytical data could be carried out. The samples collected have already been described in Section 4.1. As a result of the findings from the first study a further 24 samples were collected by both groups in February 1995 for analysis.

Results from the first comparison of data are shown in Figure 10. Very good agreement was observed for Na, Ca, Mg and Cl and the correlations were reasonably good, for NH_4 and Si although there was significant scatter around the 1:1 line.

For iron the sum of the Fe^{3+} and Fe^{2+} data reported by GSV was compared with the Fe_{total} data from BGS. Most of the values correlate well, but there is a positive bias towards the GSV data. This is probably because the samples collected for analysis by the GSV laboratory were not filtered before acidification. Where dissolved metals are to be determined it is important that all samples are filtered through a 0.45μm filter, to remove suspended matter, before acidification. Suspended matter may include particles of rust derived from pipework and this, if acidified and dissolved in the sample would produce a false high reading, which is not representative of aquifer conditions. The solubility of iron minerals is strongly influenced by pH and redox variations, with ferrous iron being dominant under reducing conditions. If the iron speciation data is to be meaningful for hydrochemical interpretation it is essential that the sample for ferrous iron analysis is stabilised in some way immediately after sampling (Cook and Miles 1980), as the very act of pumping the water to the surface disturbs the redox equilibria obtained at depth and induces oxidation of the sample. Stabilization of ferrous iron may occur in organic rich waters as it forms complexes with the organic water and is therefore held in solution at a much wider range of redox conditions. This could explain the continued presence of ferrous iron in some of the samples analysed at the GSV laboratory.

There is a large discrepancy in the data for manganese, this was thought to be as a result of the manganese dropping out of solution prior to analysis as the GSV sample was not acidified. The potassium data also does not compare well. This is surprising as K in solution is normally reasonably stable and the sodium data determined by the same method shows good correlation with BGS data. The randomness of the data implies that there are no systematic analytical problems, an error may have been introduced, perhaps from contaminated sample bottles or laboratory glassware.

The sulphate data showed poor agreement. The ICP-OES method used at Wallingford assumes that all of the sulphur in the sample is present as SO_4, which is not always the case in reducing waters. If sulphide is present in the water analysed it causes enhanced signals as it is more volatile in the plasma. To confirm the accuracy of the results the samples were re-analysed at Wallingford by ion chromatography. Figure 11 clearly demonstrates the good agreement between the two methods used at Wallingford

Only six values were quoted by GSV for NO_3. Five of the points fall quite well on a 1:1.5 BGS:GSV line. This may be as a result of a systematic analytical error, but, unfortunately no data was reported by GSV for the second interlaboratory study for a further comparison to be made.

The first comparison of data was very encouraging. Seven out of the eleven elements correlated well and where differences did occur it may have been due purely to sampling and storage techniques. For the second interlaboratory study and any subsequent sampling carried out, it was recommended that all samples be passed through a 0.45μm filter and that the sample for minor and trace metals be acidified to 1% v/v with high purity HNO_3. The importance of acid washing bottles to minimise contamination from one sampling trip to the next was also discussed.

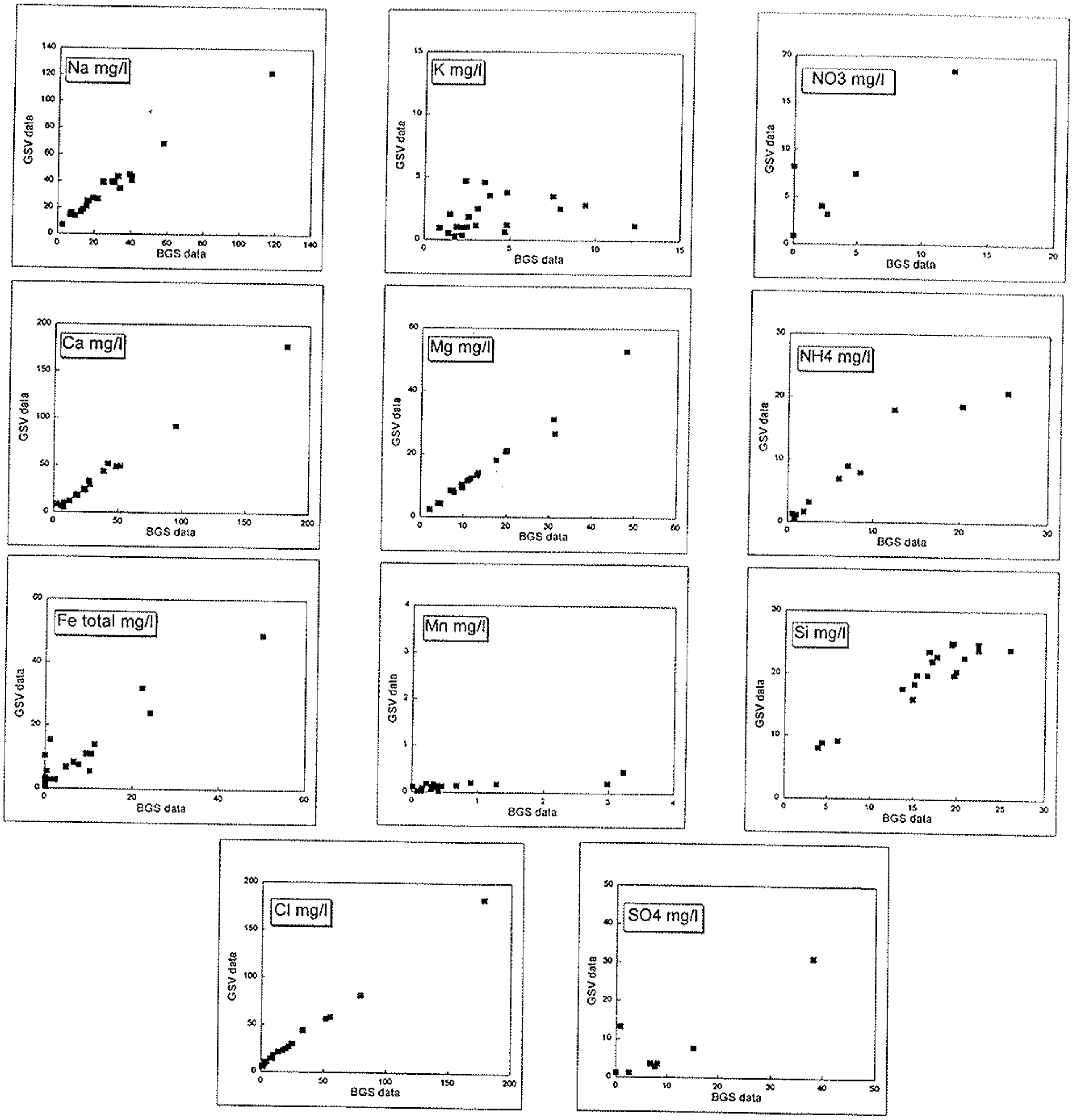


Figure 10 Data from the first interlaboratory study

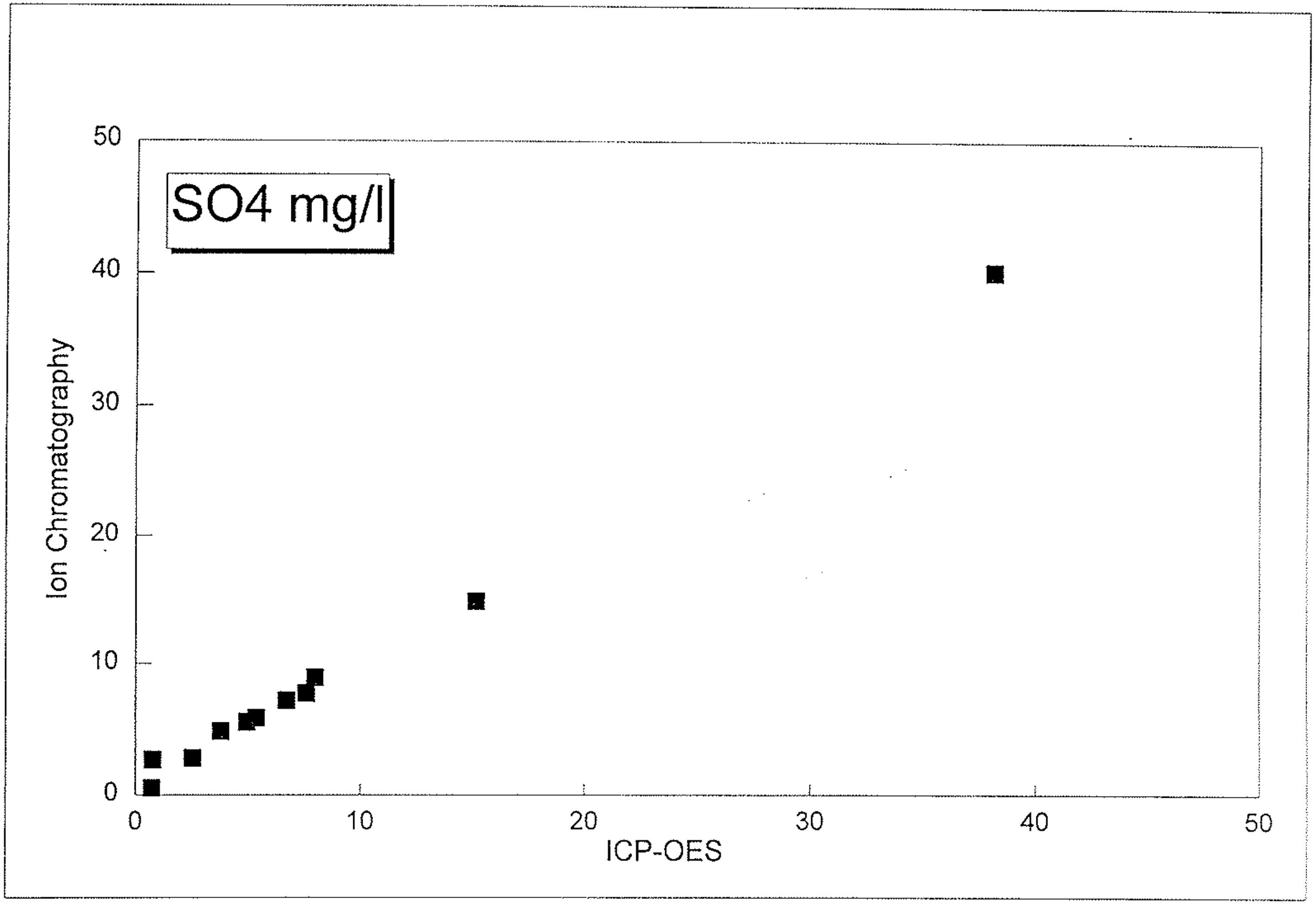


Figure 11 Comparison of sulphate data acquired at BGS using two different methods - ICP-OES and ion chromatography.

Results form the second interlaboratory study are displayed graphically in Figure 12. Sulphate and potassium still show very bad agreement, but manganese now correlates well.

4.3.2 *Field determinations*

Unstable parameters (pH, Eh, temperature, HCO_3, and DO_2) were measured on-site as was specific electrical conductance (SEC). Counterpart staff were trained for sampling techniques and the use of field equipment including the calibrating and quality control regime to be adopted. Unfortunately the trained staff were not always available to carry out the field sampling and the procedures ensuring the quality of the on-site determinations and sampling were not carried out. As a result, particularly for the samples collected in March 1995, the field data was unreliable and the samples appeared not to have been filtered correctly prior to acidification. Whilst this data has been included in the data set their absolute values must be viewed with caution.

5. GROUNDWATER QUALITY

5.1 Background

Urbanisation has important implications for groundwater quality as a result of both modification to the groundwater system and the introduction of additional sources of recharge. The quality of water recharging the aquifer beneath a city will largely depend on the source. For example, leaking water mains are generally a major source of recharge beneath cities and the quality of this water is usually excellent. This source of recharge will have a positive impact upon the quality of the underlying groundwater and will help dilute any urban derived contaminants. Conversely, seepage from on-site sanitation systems, another major source of urban recharge in unsewered cities, is normally of poor quality and leads to increasing chloride and nitrate concentrations in the underlying groundwaters.

In addition to the quality of the recharge source and its relative contribution to the overall urban water balance, physiochemical transformations of the recharging water during migration to the aquifer will also help determine the impact on groundwater quality. Various processes are possible and include degradation (eg. reduction of nitrate to nitrogen gas), sorption (eg. phosphate and some organic-metal complexes to clay minerals) and precipitation (eg. various metal ions). Previous studies have shown that there can be a serious deterioration in groundwater quality beneath many unsewered cities, including rising concentrations of nitrate (or NH_4), chloride and bicarbonate (Morris *et al*, 1994).

The objectives of the Hanoi study were:

(a) to understand the groundwater system beneath Hanoi and how it evolved;
(b) to assess the impact that urbanisation and its associated groundwater development has had on water quality beneath Hanoi;
(c) to predict future water quality trends.

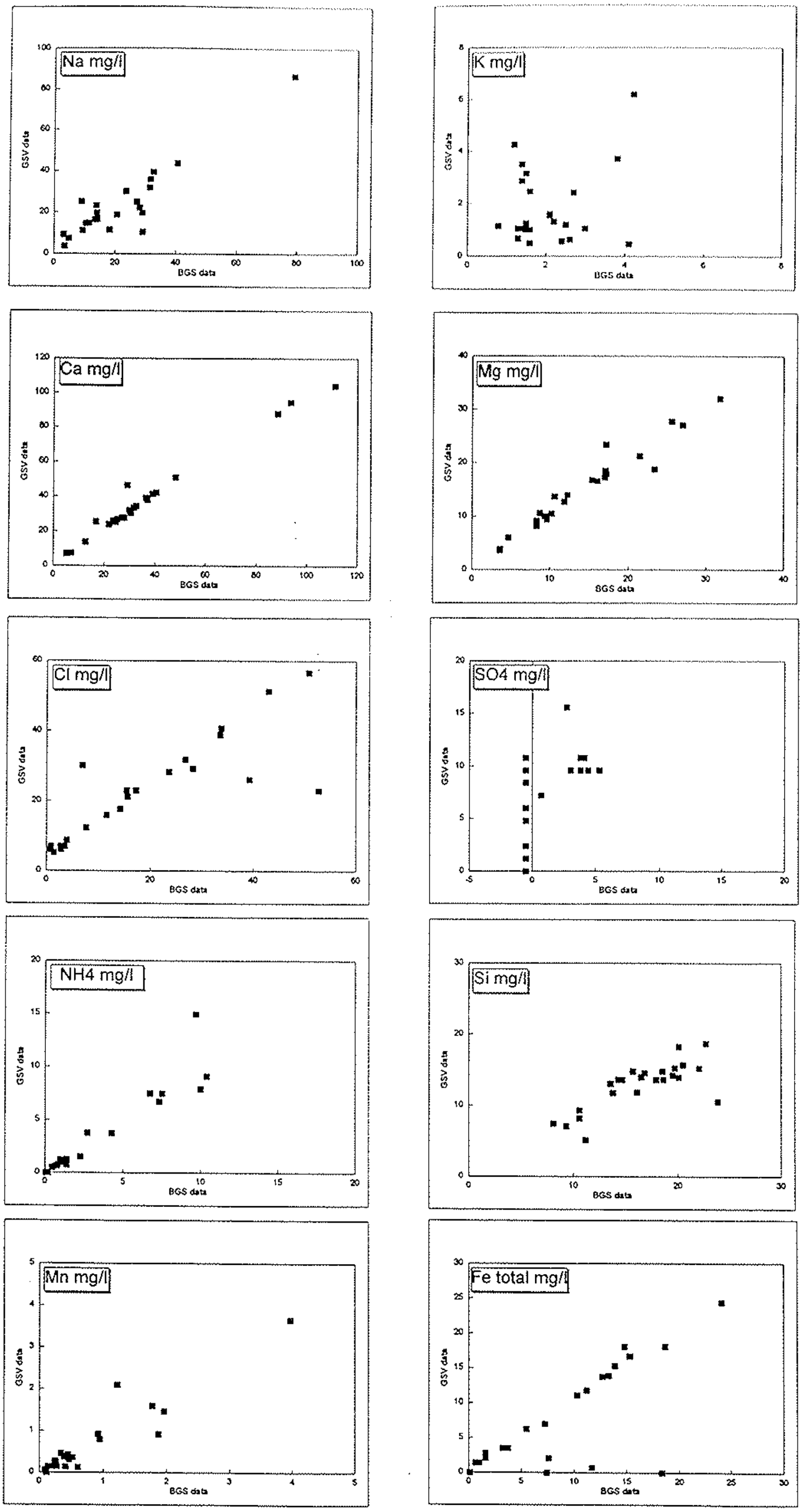


Figure 12 Correlation of data from the second interlaboratory study.

5.2 Baseline or Natural Groundwater Quality

The baseline or natural groundwater quality is defined here as the quality of the groundwater prior to significant abstraction and the modification of water quality by anthropogenic sources.

Within the Hanoi area, groundwater abstraction has removed a volume of water equivalent to three times that stored in UAS and LAS. This has ensured that the groundwater presently pumped from the LAS is of modern origin (certainly post 1950s and probably post 1970s) and has replaced the original water which was many hundreds of years old.

Natural water quality can therefore only be obtained from boreholes outside of the area of influence of pumping of the Hanoi well fields (Figure 9). However, there are few boreholes that are available for sampling outside of the city and of these some lack basic data on well design and depth and others, particularly those that penetrate the UAS only, have no pump. Although rates of pumping in these boreholes are much lower than for those in the urban well fields, it is still possible that even the quite limited pumping may have induced modern recharge and modified the water quality. The lack of sewage disposal systems in the villages and the use of chemical fertilisers and manures are all potential sources of contamination in this modern recharge.

Outside of the area of significant urban groundwater abstraction the LAS is recharged by lateral movement of low salinity water from the Red River. Infiltration from the UAS is unlikely as there is little head difference between the two aquifers, except where leakage is induced by pumping. Close to the river the groundwater in the LAS is probably recent due to interchange of water from the river system. Further away from the river system the water will become progressively older and a trend from $CaHCO_3$ to $NaHCO_3$ to NaCl dominated water types has been observed (unpublished GSV map).

Maps of selected elements for the top and main aquifers are shown in Figures 13-16 and a comprehensive table of all chemical data is listed in Appendices 1 and 2. A brief discussion of three ion species Cl, HCO_3 and N and their distribution outside the city is given below:

5.2.1 *Chloride*

The data for the UAS is rather sparse, however of the four sites sampled to the east of the Red River, three have a chloride concentration greater than 100 mg/l (Figure 13). This may be an indication that baseline levels are reasonably high. Chloride concentrations in the LAS are on average lower outside of the city. Two sites along the baseline cross section in the main aquifer (Q36 and Q127a) are dominated by the chloride and sulphate ions rather than bicarbonate ion characteristic of the LAS and may indicate leakage from the more saline upper aquifer.

5.2.2 *Bicarbonate*

Bicarbonate concentrations are significantly lower in the main aquifer to the east of the river, at around 150 mg/l (Figure 14) , compared to the average in the urban area of 250 mg/l. A couple of sites to the west of the city have elevated HCO_3 values as compared to the typical baseline concentration, perhaps an indication of leakage from the higher carbonate waters of the UAS. The pattern in the concentrations in the upper aquifer compare with those of the LAS in that the concentrations to the east of the river are again lower than those to the west.

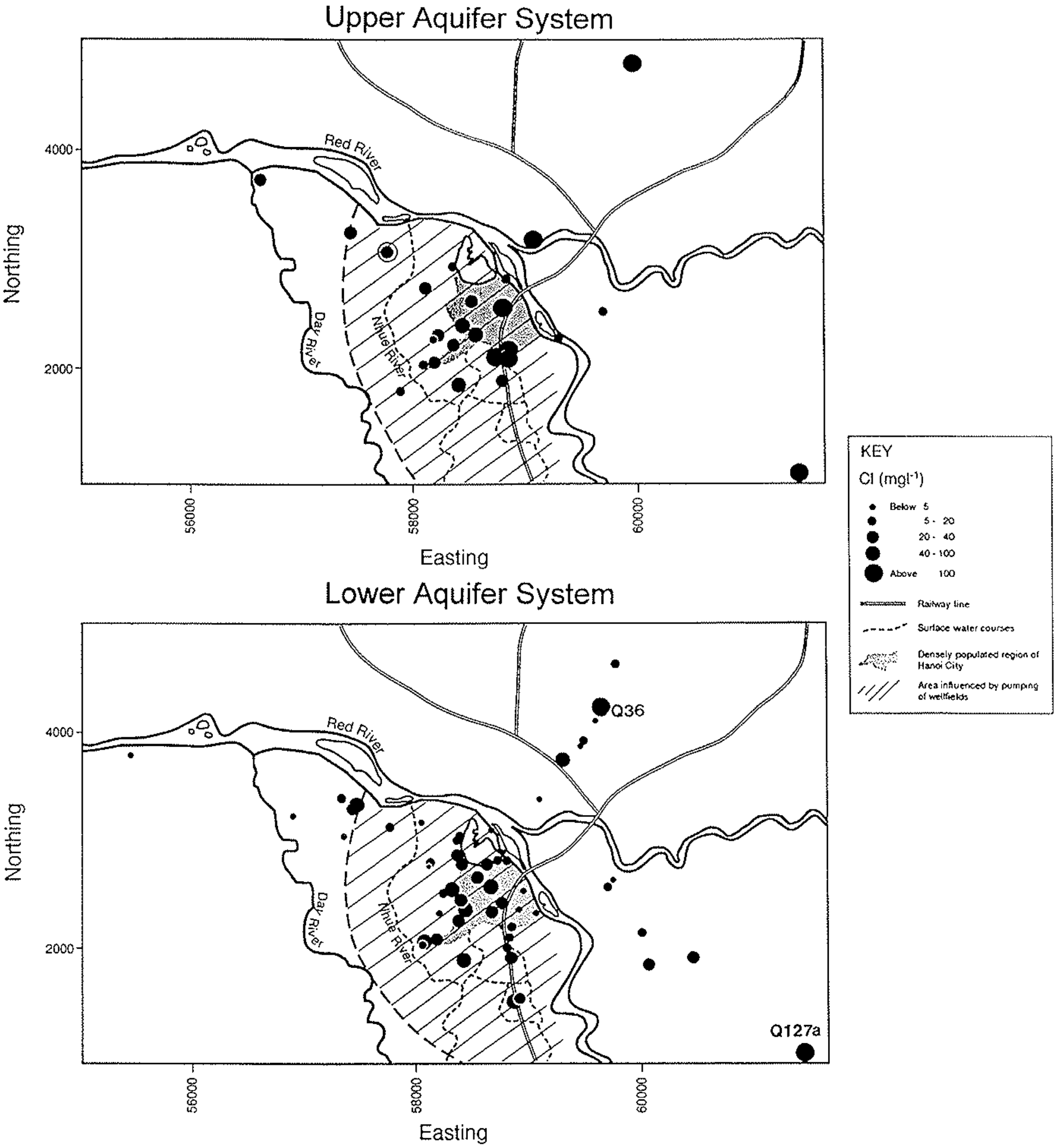


Figure 13 Concentrations of chloride in samples from the Upper and Lower Aquifer Systems

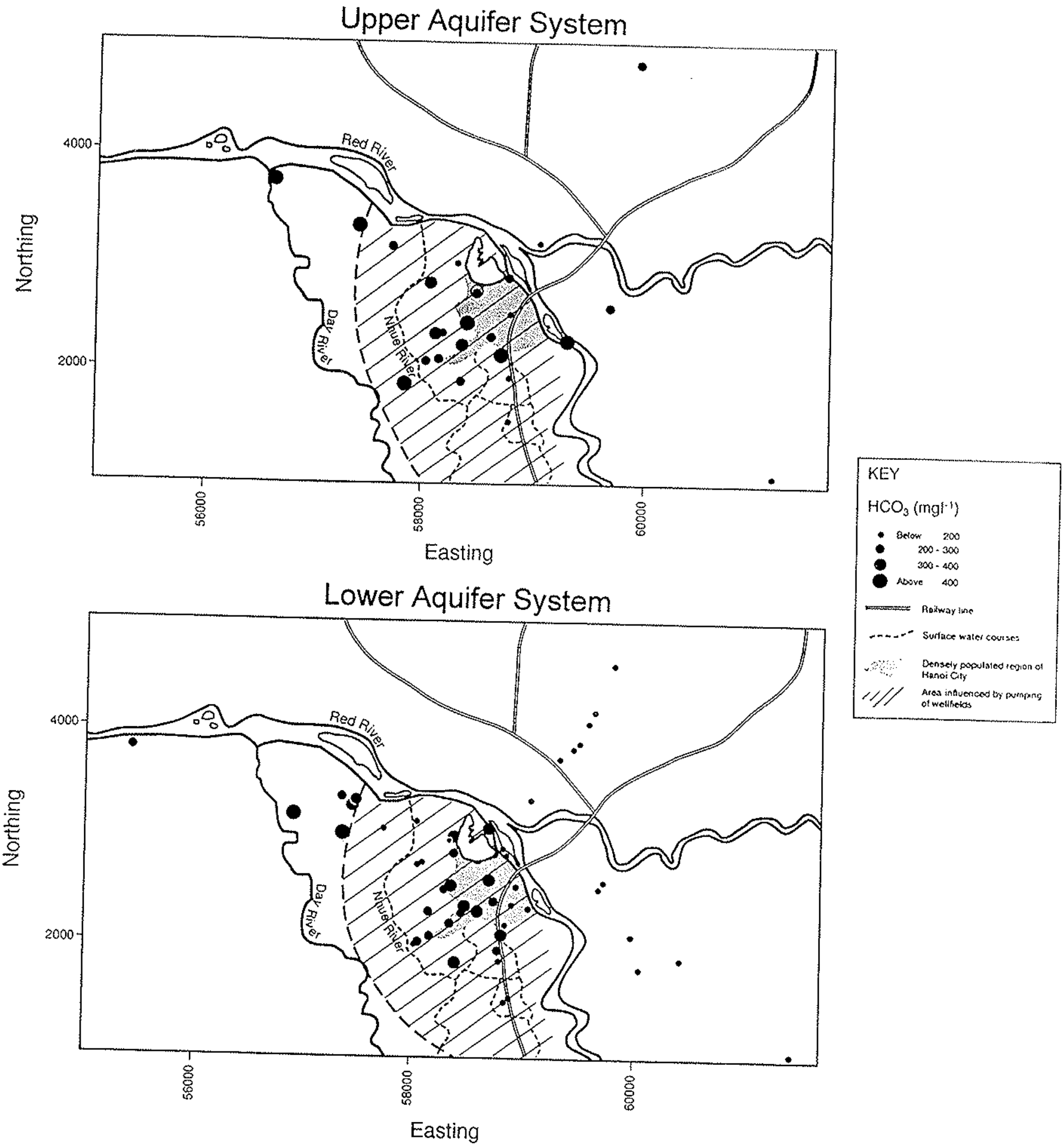


Figure 14 Concentrations of bicarbonate in samples from the Upper and Lower Aquifer Systems

5.2.3 *Nitrogen species*

Ammonium concentrations above the WHO guide value of 0.2mg/l were found in the majority of the samples collected from both the urban and rural areas (Figure 15). However nitrate is undetectable in all but a few sites (Figure 16). This is consistent with the anaerobic nature of the LAS (where any NO_3 present is likely to be reduced to NH_4) and the high organic component of the UAS, whether naturally occurring as peat layers or as a result of the continuous application of animal wastes to the agricultural areas.

5.3 Water Quality within the Hanoi City Area

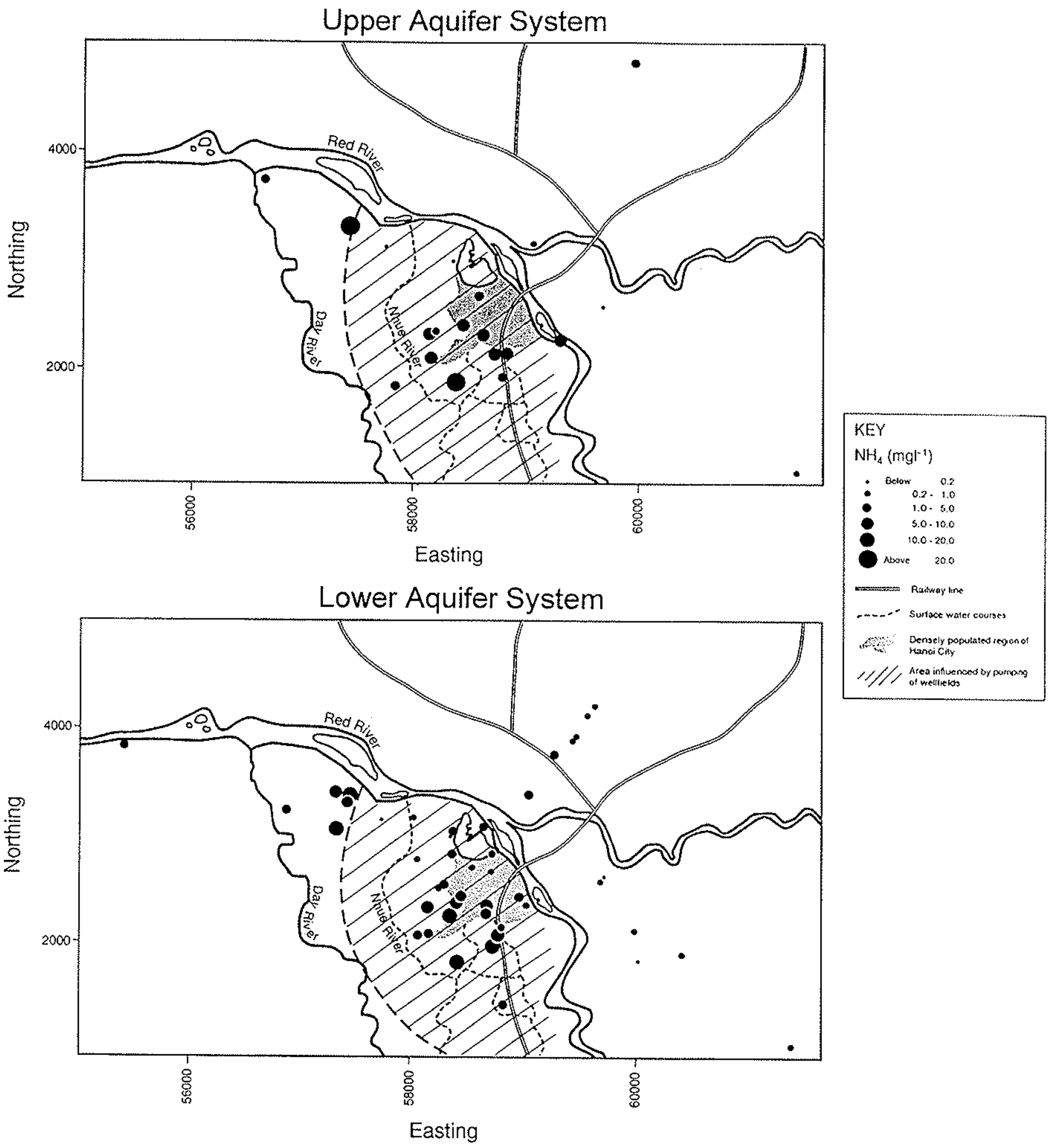
The rapid increase in abstraction rates (Figure 1) has caused large cones of depression to develop around the main wellfields (Figure 4). There is concern that this could induce recharge of poor quality water as a result of urban wastewater disposal. The cones of depression are so pronounced that the natural groundwater flow regime in both aquifers (north-west to south-east)no longer exists; any contaminants that percolate through the upper layers will no longer be flushed through laterally but will remain trapped, moving downwards in response to pumping. Calculations have shown (Section 3.2) that the amount of water abstracted in the last 84 years far exceeds the storage capacity of the two aquifer systems, it must be assumed therefore that the water pumped today is of very recent origin.

5.3.1 *Chloride*

Elevated chloride concentrations can be an indicator of contamination, however as mentioned in Section 5.2 it is thought that the baseline concentration for the UAS is also high. This makes it difficult to assess whether high chloride concentrations in groundwater beneath the city are a result of anthropogenic activity or due to incomplete flushing of older water from the system. In the urban area (Figure 17) the highest chloride concentrations (i.e. all above 100 mg/l) occur to the south near to Tuong Mai pumping station where clay layers above the main aquifer are thickest. It is possible that either 'old' waters trapped between the clay layers have not been fully flushed by pumping or that contaminated waters have migrated from the surface. The thick clay layers appear to effectively protect the underlying Hanoi aquifer since chloride concentrations immediately beneath this area are not high.

The Red River is a significant source of good quality recharge water and this can clearly be seen in Figure 16 where the lower chloride concentrations are found at those sites closest to the Red River. This natural regime is to be exploited soon by the development of two new wellfields along the flood plain which will purposely induce leakage from the river and make use of the natural filtration afforded by the alluvial deposits to remove microorganisms and the high suspended load in the river.

The To Lich and Lu Rivers, the main waste water canals for the city, have the highest chloride of the surface waters sampled. The To Lich River gradually increases in concentration downstream from 25mg/l, just south of Ngoc Ha pumping station, to 58.5 mg/l at its junction with the Nhue River. The Lu River sample also contained about 50 mg/l Cl (Appendix 5). These values, although significantly higher than those found in the Red and Nhue Rivers, are not elevated enough to cause enhancement of aquifer concentrations as a result of downward leakage, given that there will be considerable dilution from other sources of recharge. The Red River and the leaky public water supply system, in particular, provide large volumes of good quality recharge water.


Upper Aquifer System

Lower Aquifer System

Figure 15 Concentrations of ammonium in samples from the Upper and Lower Aquifer Systems

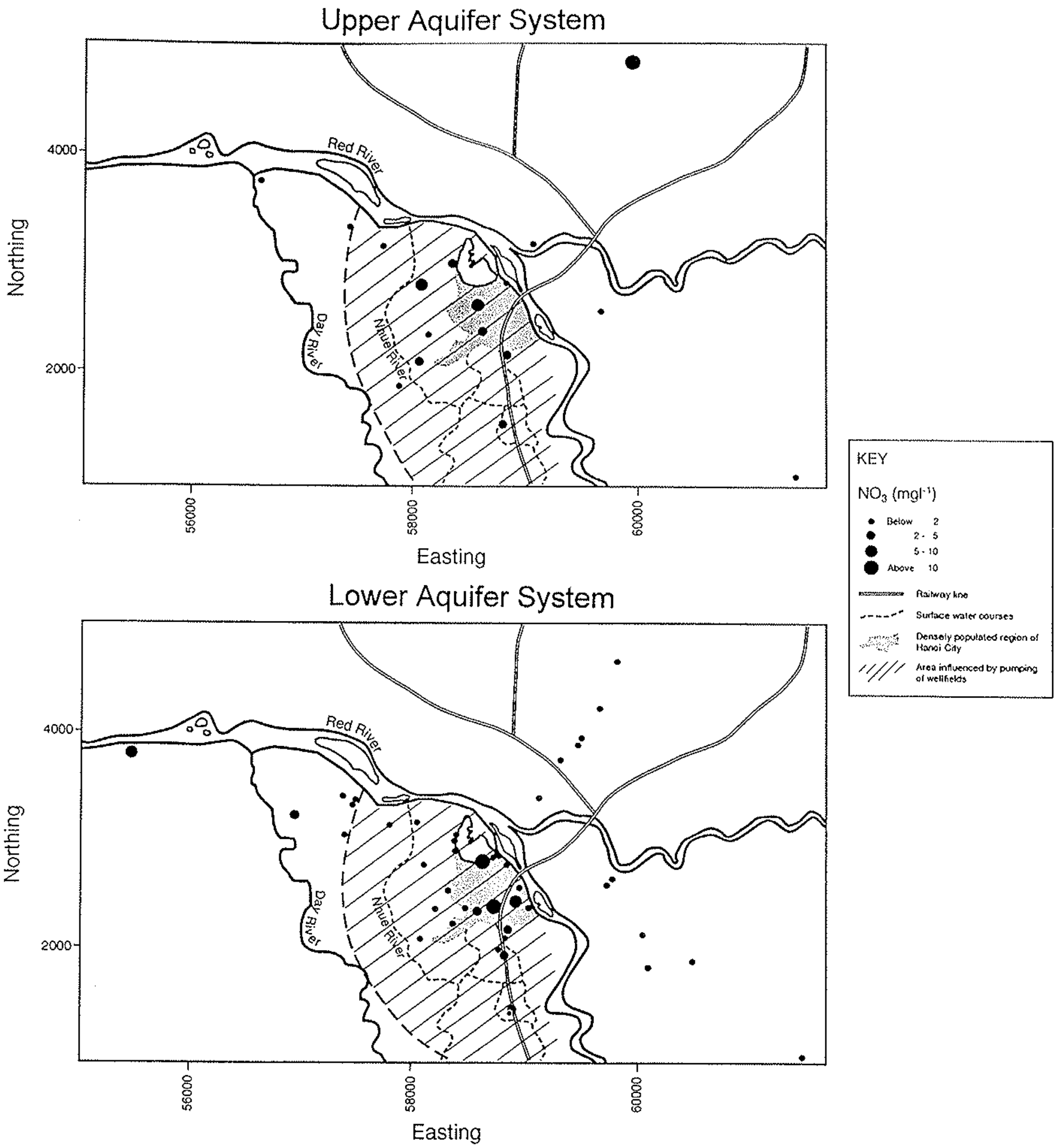


Figure 16 Concentrations of nitrate in samples from the Upper and Lower Aquifer Systems

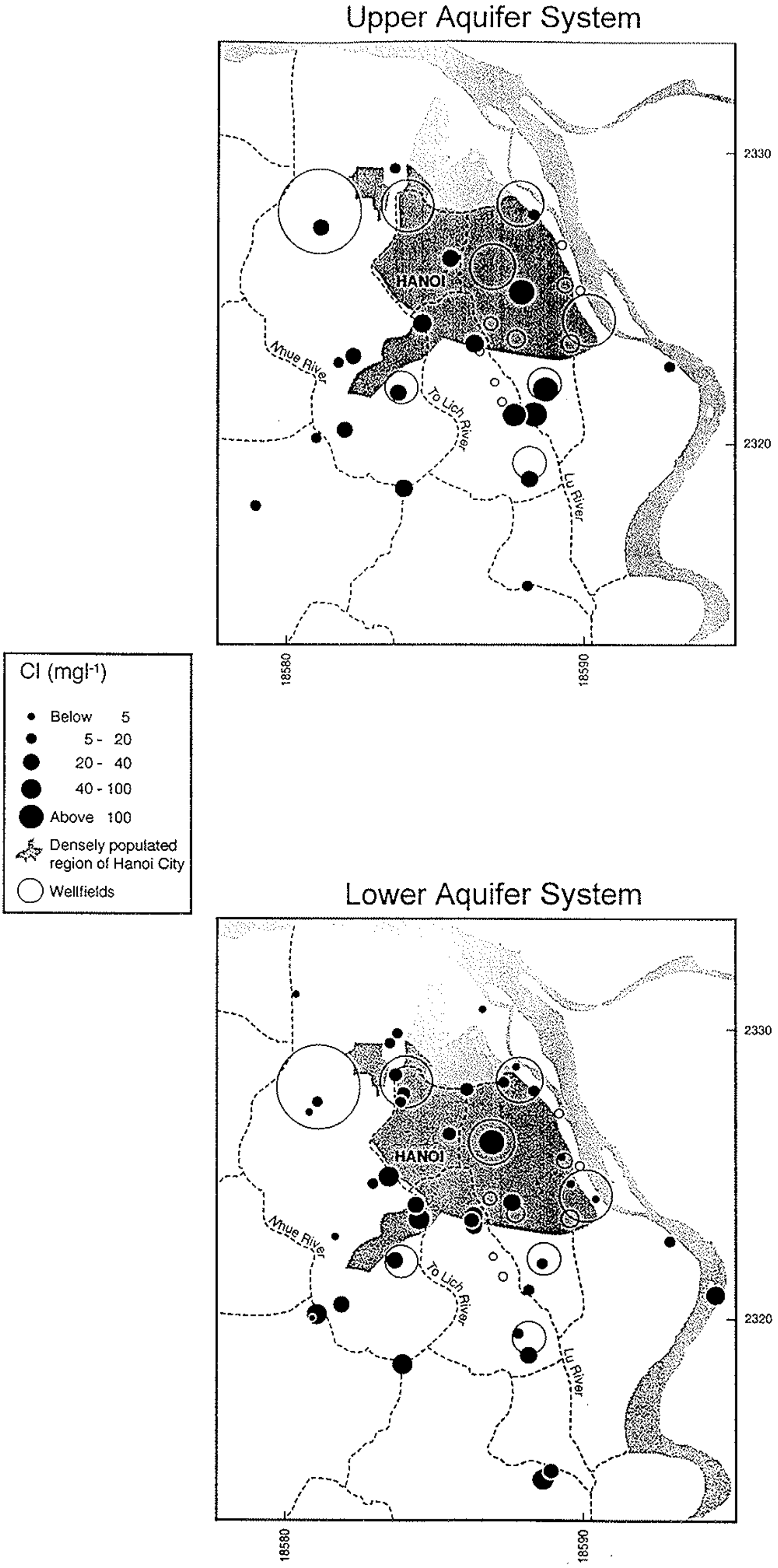


Figure 17 Chloride concentrations in the urban area

5.3.2 *Bicarbonate*

Beneath unsewered cities it is not unusual to find a significant increase in HCO_3 as a result of production of CO_2 from the oxidation of the increased organic load. This organic matter is derived from wastewater disposal to both the ground and to surface waters. Within the urban area of Hanoi the groundwater in the top aquifer has slightly higher concentrations of bicarbonate than the lower aquifer, which may be an indication of a small enhancement due to urban wastewater disposal. Total organic carbon (TOC) and $^{13}C_{DIC}$ (dissolved inorganic carbon) were determined on samples from a selection of sites within the urban area (all from the LAS except Lin Nam Thanhi) see Appendix 6. When HCO_3 and TOC are plotted against $\delta^{13}C_{DIC}$ concentration a strong relationship is seen between TOC and HCO_3 (see Figure 18). As TOC concentrations increase the potential for fermentations to CH_4 is greater, which results in a rise in $^{13}C_{DIC}$ and HCO_3. This is an indication that the HCO_3 in the water is derived from organic components (natural or anthropogenic) and not water rock interaction. Outside of the city bicarbonate concentrations are similar in both aquifer systems (Figure 14).

5.3.3 *Nitrogen species*

Most samples were analysed for both NH_4 and nitrate as these parameters are important indicators of human waste pollution. Nitrate was either very low or undetectable in all of the groundwaters, but was considerably higher in the samples taken from the waste water canals. Conversely ammonium in most cases was well above the WHO guide value of 0.2 mg/l in the groundwaters (Figure 19) and undetectable (except for one site) in the surface waters. This is consistent with the anaerobic nature of the LAS (where any NO_3 present will be reduced to NH_4) and the highly organic nature of the upper layers in the north west of Hanoi and the 4 urban districts of the city. The concentrations of NH_4 in both aquifers are similar; the data collected during this study indicates that higher concentrations generally occurred in the LAS, whereas historical data (Tong Ba Lan *et al*, 1996) indicates that the opposite is true.

There is an abundance of iron in the waters which in reducing environments will be present as Fe^{2+}. Nitrate can be removed by reacting with iron in this oxidation state to form iron oxides and ammonia, the reaction being accelerated by the presence of traces of oxygen. It is possible that this is the process taking place in this area.

The areas where peat layers are thickest corresponds to the region of greatest combined clay layers above the LAS. Figure 20 shows that in these regions the NH_4 concentrations are higher and that whilst some of the nitrogen may be from anthropogenic contamination it is possible that the formation of NH_4 is due in part to the naturally high organic content of the aquifer.

5.3.4 *Other metals*

The majority of minor samples analysed had either very low concentrations of minor and trace metals or were below the detection limits (Appendices 3 and 4) It appears therefore that no heavy metal contamination is reaching the aquifer systems. Organic rich soil is very efficient at sorbing metals and it may be that any contamination that does enter the unsaturated zone is trapped within this layer and does not readily infiltrate to the water table. The elements detectable in most of the samples were Si, Ba, Sr, Mn and Fe, which appear to be naturally occurring as there is little difference between the concentrations found in and outside of the city and their concentrations in the surface waters, including the waste water canals are lower than in the groundwaters. Of some concern is the level of iron in the waters. Whilst iron is not known to have any directly detrimental effects on human health and is easily removed by aeration after abstraction, it can cause well failure by clogging of well screens and pipe work.

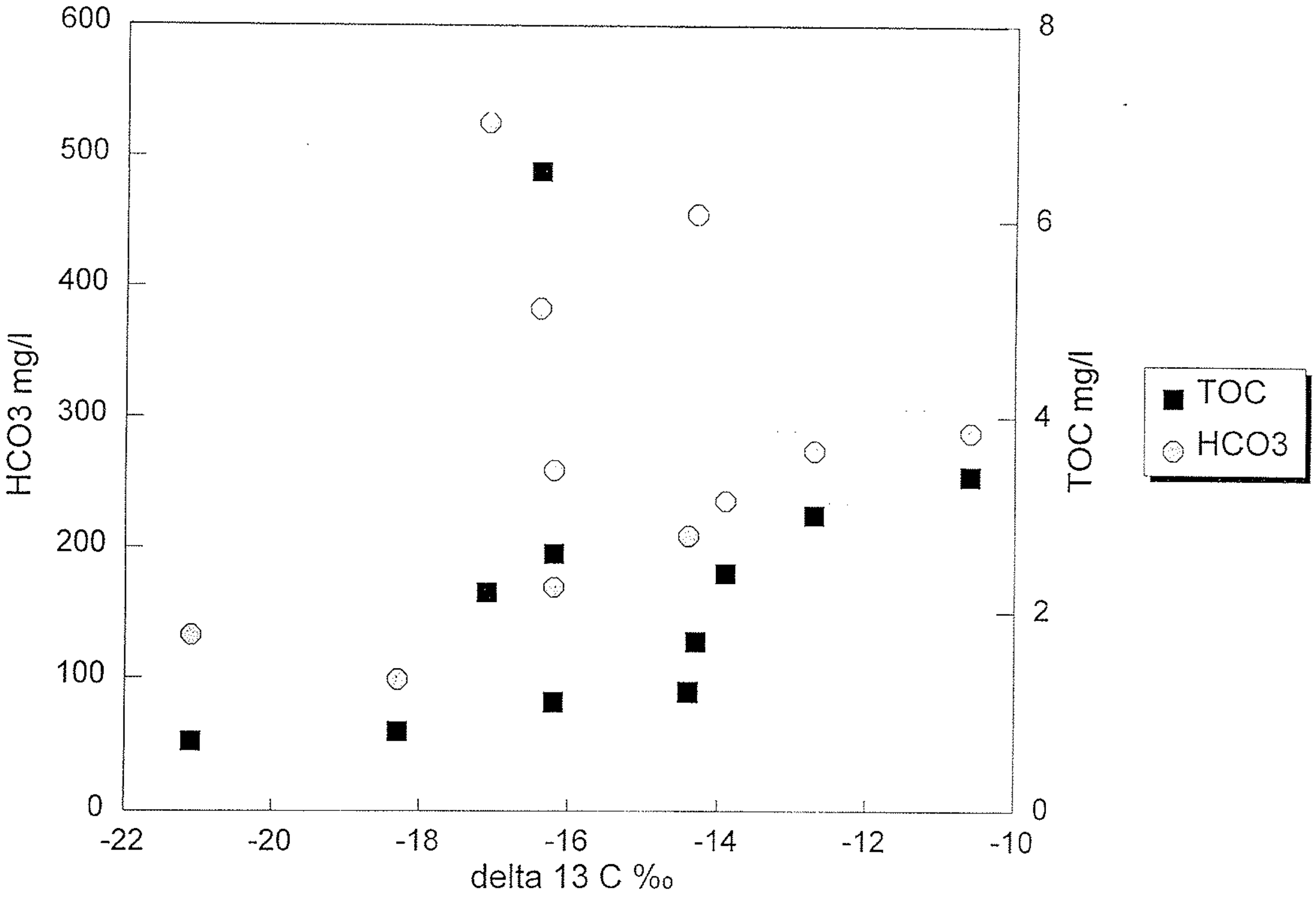


Figure 18 Graph of TOC and HCO_3 plotted against $^{13}C_{DIC}$ concentrations

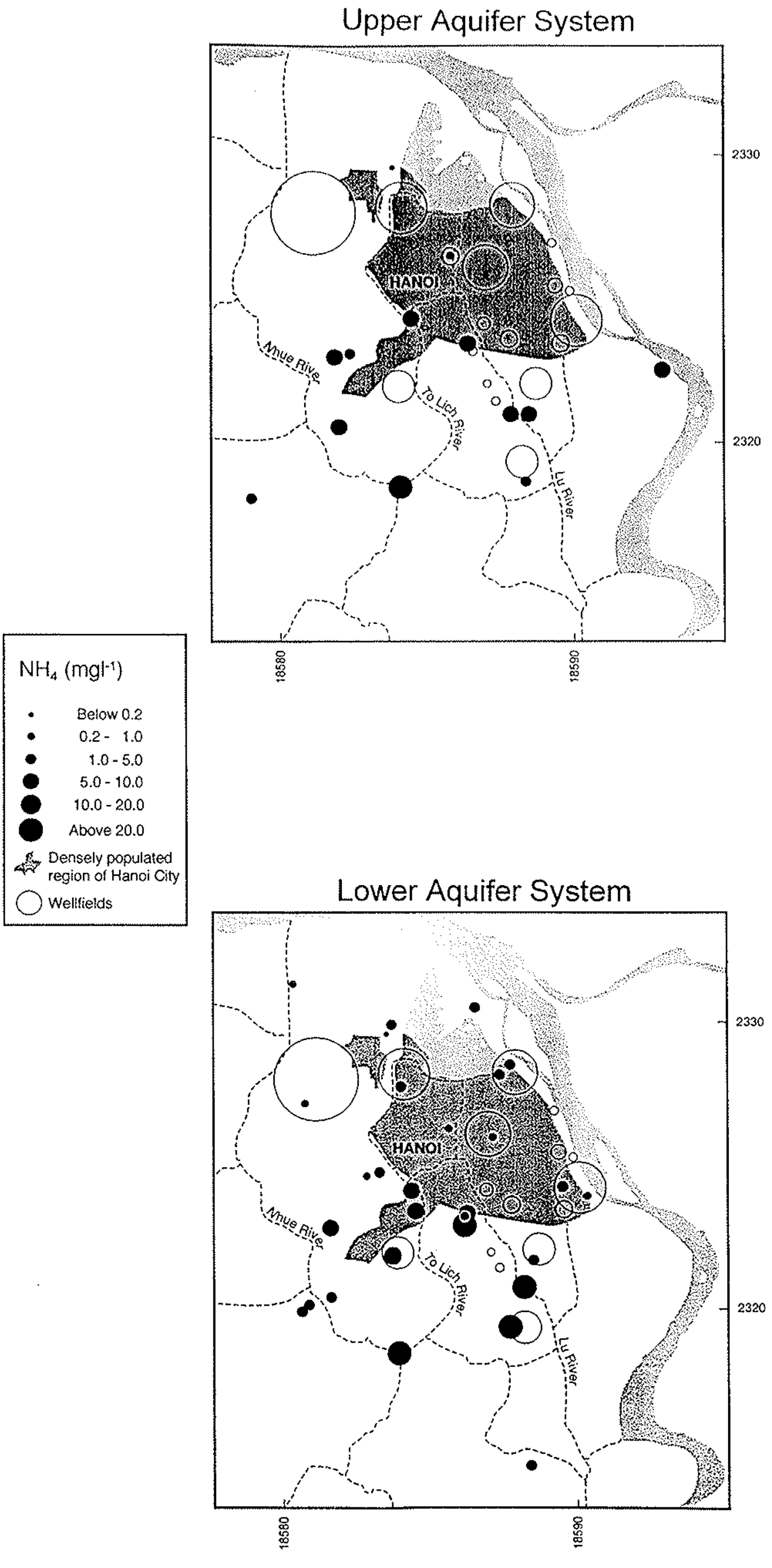


Figure 19 Ammonium data for samples collected from the Upper and Lower Aquifer Systems in the urban area

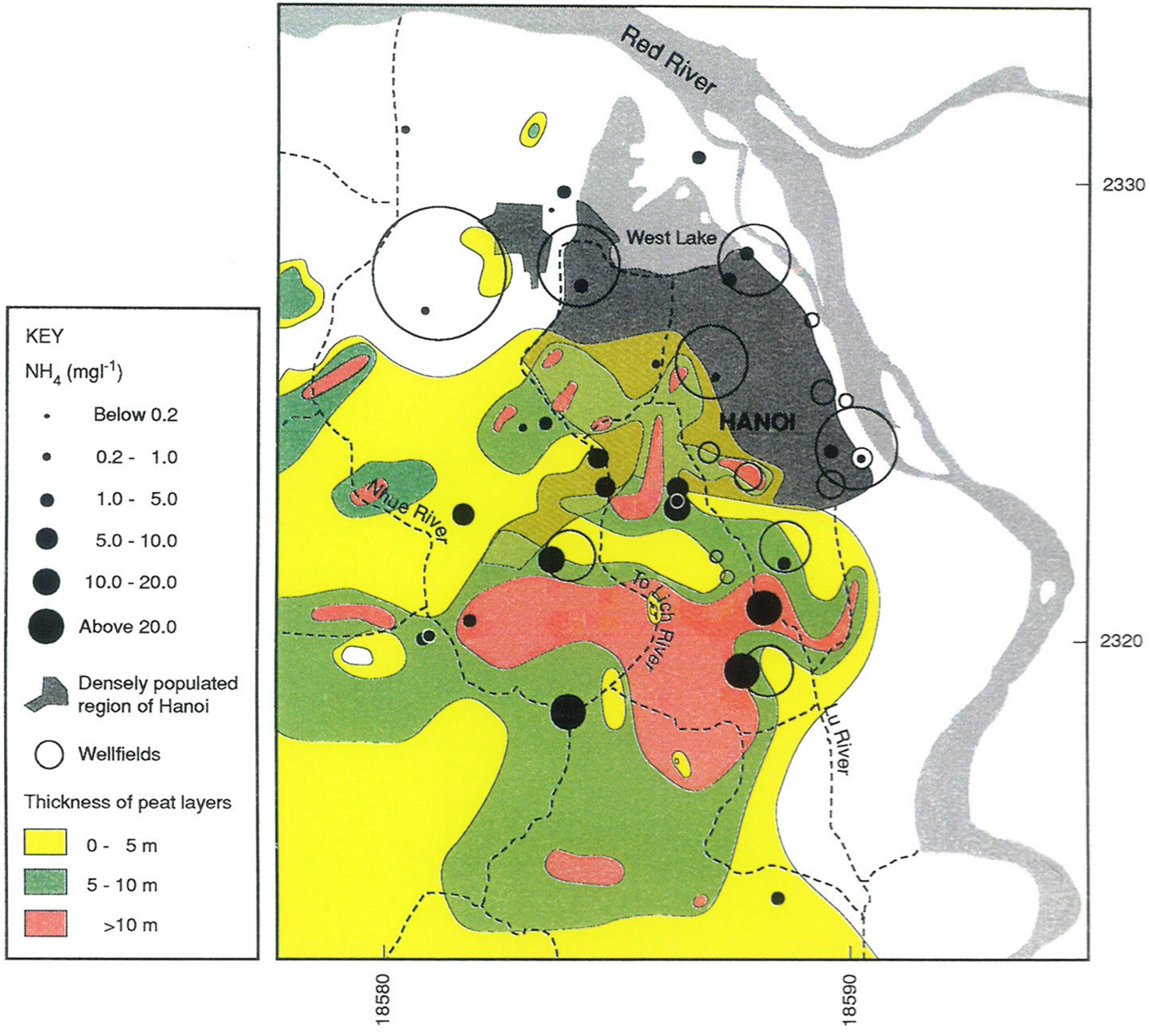


Figure 20 Map showing high ammonium concentrations occurring in the LAS in the regions where the peat layers are thickest

5.3.5 *Stable Isotopes*

With the aim of establishing the source of the groundwater beneath Hanoi a limited study of the stable isotopes of deuterium (δ^2H) and oxygen ($\delta^{18}O$) was carried out. Samples were taken from selected surface water sites and from boreholes exploiting the UAS and LAS over the whole study area. See Appendix 6 for a tabulation of the data and details of site locations.

A plot of the data (Figure 21) shows a large range of values with some samples being 'light' (isotopically depleted). The majority plot close to the Bangkok MWL (meteoric water line), but there is no distinct grouping of the different groundwater types. This may indicate mixing of waters. A more extensive study would need to be carried out in order to more fully understand the processes involved.

6. DISCUSSION

The hydrogeology of the Hanoi and Bacbo plain area is complex and it has been difficult to define the natural background chemistry. Access to the GSV Hanoi Monitoring Network database was granted but it was decided that the inorganic chemistry data from the current sampling only would be used for interpretation to preserve the consistency of the data set. The sparsity of data therefore, particularly for the upper aquifer, has allowed only a general overview of the water quality to be obtained.

It is important to recognise that groundwater beneath Hanoi is a mix of water of different origins and includes:

(i) good quality (low chloride) infiltration from mains leakage and rainfall

(ii) poor quality (higher chloride) seepage from on-site sanitation systems and from wastewater canals

(iii) good quality (low chloride) recharge from the Red River.

In areas close to the Red River or where the UAS is relatively permeable, complete flushing of the UAS and LAS by modern recharge is likely. However, where thick clay layers are present within the UAS, flushing by modern recharge may be less complete and some older, possibly more chloride-rich groundwaters, may be retained. For these reasons ascribing with confidence, an origin to groundwater in such a complex system, based on water quality is not possible. However some broad statements can be made.

(a) The substantial abstraction of groundwater from beneath Hanoi in the second half of the 20th century has resulted in replacement of original groundwater by modern recharge due to induced leakage.

(b) There is some evidence of pollution in the UAS with slightly elevated concentrations of HCO_3 and Cl. The extent of the pollution is surprisingly low given the high population density and the lack of any formal sewage treatment system. This may be because the aquifer is recharged by much larger volumes of good quality water (rivers, leaking public supply pipes and rainwater) than poor quality water (leaking sanitary systems or waste water canals) or as a result of sorption of metals by the highly organic soil layers.

(c) There is no evidence of groundwater contamination by metals derived from industry. Sorption of metals to the highly organic soil and the normally neutral pHs of the groundwaters are contributing factors.

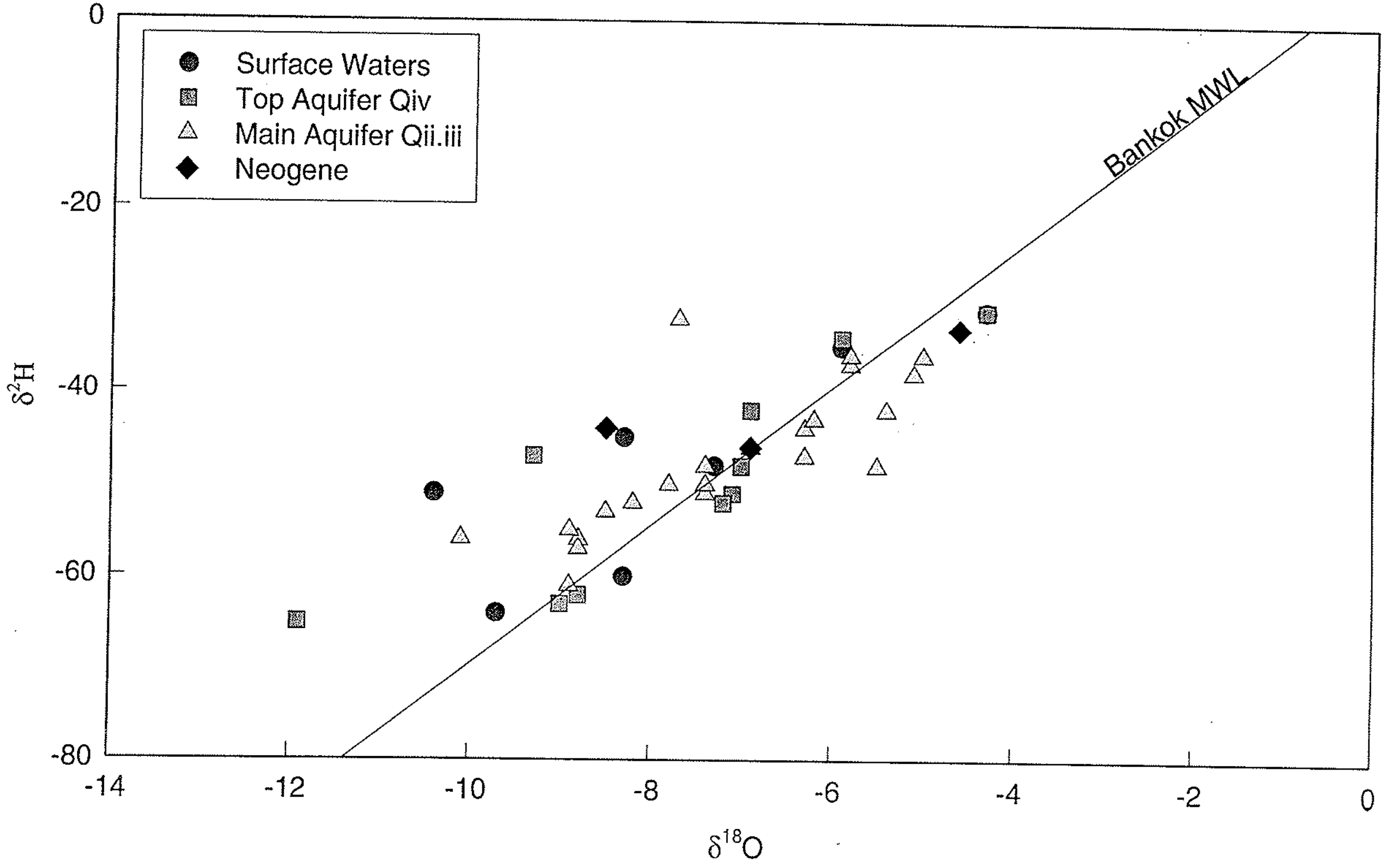


Figure 21 Correlations of the stable isotopes of deuterium (δ^2H) and oxygen ($\delta^{18}O$) in relation to the Bangkok meteoric water line (MWL).

(d) Significant and troublesome concentrations of ammonia are observed in both the LAS and UAS, especially to the south of the city. Whether this is predominantly due to the reduction of nitrate (to ammonia) from urban wastewaters or the oxidation of naturally occurring organic rich peat layers is unclear although the association of higher ammonia concentrations in areas where the peat is thickest would suggest that the latter is more likely.

(e) A widespread and substantial deterioration in groundwater quality beneath Hanoi is unlikely, at least in the near future. It is important to consider the geology and hydrogeology in urban planning and development to avoid problems of localised contamination, for example, the location and design of landfills.

For the future it is essential that the groundwater quality in both aquifer systems is carefully monitored so that any deterioration in water quality can be observed and acted upon. Monitoring of the UAS is especially important since this provides an early warning of possible quality changes to the deeper aquifer that may be caused by induced leakage. The Hanoi Monitoring Network already set up goes a long way to meeting this objective, however a strict quality controlled procedure needs to be enforced to ensure that data representative of the water in the aquifer is obtained. Sampling can sometimes be the single largest source of error in a hydrochemical study, and it is imperative that a strict regime is followed, (Cook, Edmunds *et al* 1989).

7. CONCLUSIONS

Large volumes of good quality groundwater present in unconfined and semi-confined aquifers underlie the city of Hanoi. Pumping in the second half of this century has induced substantial leakage and the groundwater beneath the city has been largely replaced by modern (post 1950) recharge. The high quality of the groundwater, despite the lack of a sewerage system, is maintained because of the considerable infiltration of low chloride recharge from the Red River and from leaking water pipes.

The increase in bicarbonate and chloride beneath the city indicates that incipient contamination of groundwater by wastewater is probably occurring.

The main water quality concerns at present are high ammonia and iron. Ammonia which exceeds the drinking water guideline value, has a health implication. Iron does not present a health problem, but can cause a bad taste and staining. The iron is most probably of natural origin but it is uncertain whether the high ammonia is due to anthropogenic influences or is naturally occurring at such high levels.

Given the value of the groundwater resource to Hanoi it is important that the aquifers are protected. Such protection measures include (a) giving full consideration to the underlying geology in planning urban development (thus avoiding locating potentially polluting activities in areas where the underlying groundwater is especially vulnerable) and (b) monitoring of groundwater to provide an 'early warning' of water quality deterioration.

8. ACKNOWLEDGEMENTS

We are indebted to the staff of the Geological Survey of Vietnam for their support and cooperation in the organisation of visits and fieldwork in Hanoi. Particular thanks go to the Director General of the Hydrogeology Division No: 2 Eng Tong Ba Lan, and to Mr Nguyen Van Dan, Mrs Nguyen Thi Ha and Mr Tran for sharing with us their extensive hydrogeological and hydrochemical knowledge of the area.

The advice and comments from W G Darling and D C Gooddy of the Hydrogeology Group, BGS have been much appreciated.

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APPENDICES

Baseline Sites

Locality	Easting	Northing	Date Sampled	T°C	Ph Field.	Ph Lab.	Eh mV	DO_2	TOC	SEC μS/cm	HCO_3	Na	K	Ca	Mg	Cl	NO_3	NH_4	SO_4	P_{total}
Upper Aquifer System																				
Q127	1861450	231030	March 1995	25.3	5.97	7.97	nd	0.9	nd	nd	95.7	91.5	3.5	14.4	8.8	165.0	-0.9	0.86	-0.5	-0.5
Q120	1859718	232533	March 1995	nd	nd	8.42	nd	nd	nd	nd	228.0	38.4	2.4	43.2	13.1	8.3	-0.9	0.16	7.5	-0.5
Q32	1859100	233140	March 1995	nd	nd	5.12	nd	nd	nd	nd	-1.0	149.0	2.7	29.2	32.8	195.0	-0.9	0.98	243.0	-0.5
Q38	1859982	234810	March 1995	nd	nd	8.05	nd	nd	nd	nd	225.0	53.1	1.3	79.6	35.0	153.0	30.5	2.20	27.8	-0.5
Q62*	1857770	233104	March 1995	25.4	9.80	8.49	nd	1.6	nd	nd	268.0	34.6	1.7	6.5	9.6	40.0	-0.9	0.13	3.8	1.3
Q69*	1857906	231816	March 1995	26.5	6.27	8.20	nd	0.8	nd	nd	809.0	44.1	5.2	96.2	29.3	9.0	-0.9	3.34	6.2	-0.5
Q57	1857456	233296	March 1995	25.7	6.38	8.30	nd	0.8	nd	nd	416.0	30.3	4.3	54.1	13.6	28.5	-0.9	48.60	2.3	-0.5
Q56	1856646	233732	March 1995	25.9	6.71	8.24	nd	0.8	nd	nd	427.0	24.0	2.9	132.0	29.0	39.5	-0.9	3.10	-0.5	-0.5
Lower Aquifer System																				
Q37a	1859800	234620	June 1994	27.0	6.01	nd	228	3.8	nd	nd	36.0	9.4	2.2	2.6	2.2	7.2	-1.8	-0.03	0.7	-0.5
Q34a	1859300	233720	June 1994	27.0	6.38	nd	127	1.9	nd	nd	142.0	40.3	3.5	17.5	9.6	79.5	-1.8	2.58	-0.5	-0.5
Q33a	1859100	233360	June 1994	27.5	6.27	nd	162	1.4	nd	nd	84.7	6.8	1.9	8.0	4.3	1.5	-1.8	1.97	-0.5	-0.5
G1 HOAI DUC No:7	1857360	233020	June 1994	27.0	6.88	nd	nd	nd	nd	nd	418.0	24.8	2.4	51.5	17.6	2.8	-1.8	12.60	-0.5	1.7
MAI DICH No:5	1858098	232732	June 1994	27.0	6.20	nd	325	1.4	nd	nd	174.0	33.8	1.5	12.5	11.8	2.8	-1.8	0.81	-0.5	-0.5
324	1858872	231468	June 1994	28.0	6.74	nd	103	1.5	nd	nd	192.0	57.6	3.1	18.4	9.9	51.8	-1.8	1.02	-0.5	-0.5
PHANG ARMY CAMP	1856915	233200	February 1995	nd	6.8	nd	nd	nd	1.7	661	455.0	10.5	1.5	93.6	25.5	2.8	4.9	3.51	-0.5	0.6
TAN LAP DAN PHUONG	1857472	233341	February 1995	26.7	7.0	nd	48	-0.1	6.5	698	383.0	79.1	1.2	38.8	17.0	43.0	-0.9	12.86	-0.5	2.2
DAN HOAI ST. No:38	1857360	233378	February 1995	26.4	6.4	nd	117	-0.1	2.4	397	236.0	23.5	1.6	36.9	11.8	17.2	-0.9	5.46	-0.5	-0.5
CENTRE FOR VEG.	1860060	231800	February 1995	26.4	6.3	nd	nd	nd	0.8	213	98.7	32.5	2.6	5.3	3.6	23.6	-0.9	0.08	-0.5	-0.5
MAPPING DIV. No:462	1860010	232100	February 1995	25.5	6.2	nd	372	2.6	2.0	228	136.0	23.6	4.1	12.7	10.6	15.6	-0.9	0.59	3.8	-0.5
AGRICULTURAL COLLEGE	1859742	232586	February 1995	26.0	6.3	nd	216	-0.1	0.7	185	132.0	28.0	2.4	6.2	3.7	3.6	-0.9	0.15	-0.5	-0.5
QUANG BA HOTEL No:62	1858394	233000	February 1995	24.3	6.8	nd	nd	nd	1.4	484	391.0	14.1	2.2	88.4	21.4	11.6	-0.9	1.27	-0.5	-0.5
YENPHONG - HABAC	1859600	234100	February 1995	25.3	6.0	nd	121	0.1	nd	136	96.3	9.5	1.4	7.0	4.7	0.8	-0.9	0.21	-0.5	-0.5
VANHA - DONGANH	1859500	233900	February 1995	24.7	6.3	nd	131	2.0	nd	244	147.0	13.5	1.3	26.9	8.7	7.7	-0.9	0.86	0.7	-0.5
Q68b	1858110	232040	March 1995	25.9	6.20	8.16	nd	0.6	nd	nd	259.0	40.0	2.2	43.4	21.3	50.0	-0.9	2.38	5.2	0.9
Q119b	1860450	231870	March 1995	25.2	5.81	nd	nd	1.0	nd	nd	136.0	37.6	3.4	13.2	7.2	31.8	-0.9	0.33	2.1	-0.5
Q120b	1859718	232533	March 1995	26.0	nd	nd	nd	0.5	nd	nd	150.0	30.8	3.3	7.8	4.1	5.8	-0.9	0.21	0.8	-0.5
Q127a	1861450	231030	March 1995	25.6	5.75	nd	nd	0.8	nd	nd	123.0	316.0	15.5	96.1	121.0	166.0	-0.9	0.35	1010	-0.5
Q62a*	1857770	233104	March 1995	26.0	9.06	nd	nd	1.6	nd	nd	150.0	33.9	2.1	8.9	9.1	5.8	-0.9	0.02	7.2	2.7
Q35	1859467	233849	March 1995	25.7	5.10	8.05	nd	1.6	nd	nd	167.0	13.3	1.3	28.9	8.3	4.5	-0.9	0.85	0.6	-0.5
Q36	1859654	234199	March 1995	nd	nd	3.52	nd	nd	nd	nd	-1.0	162.0	2.3	18.8	30.8	195.0	-0.9	0.62	268.0	-0.5
Q67a	1858685	233075	March 1995	25.9	6.74	nd	nd	1.0	nd	nd	302.0	7.0	1.9	62.2	19.4	1.8	-0.9	1.11	5.1	-0.5
Q57a	1857456	233296	March 1995	27.2	6.91	8.36	nd	0.5	nd	nd	148.0	40.4	2.8	58.4	21.4	24.3	-0.9	9.57	-0.5	-0.5
Q173	1855450	233800	March 1995	22.4	9.20	8.20	nd	7.6	nd	nd	299.0	11.3	1.8	96.8	23.1	3.5	6.6	3.14	-0.5	-0.5

Appendix 1: Major element data for baseline sites. All data is as mg/l unless otherwise indicated. Negative values indicate the lowest quotable concentration. Parameters not determined are indicated by: nd. Sites marked with a * just fall within the zone of influence for pumping of the well fields.

Baseline Sites

LOCALITY	B	Li	Si	Sr	Be	Ba	Sc	Y	Mn	Co	Fe_{total}	Zn	V	Cd	La	Cu	Zr	Cr	Ni	Mo	Al	Pb
Upper Aquifer System																						
Q127	-0.03	-0.007	20.3	0.136	-0.001	0.130	-0.002	-0.003	0.907	-0.02	26.60	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q120	0.09	-0.007	20.9	0.150	0.002	0.628	0.005	0.020	1.790	-0.02	18.60	0.13	0.04	-0.03	0.04	0.05	-0.02	-0.04	0.05	-0.1	6.4	-0.2
Q32	0.04	0.008	10.0	0.149	-0.001	0.101	-0.002	0.007	3.280	0.09	25.70	0.12	-0.02	-0.03	-0.02	0.03	-0.02	-0.04	0.13	-0.1	0.7	-0.2
Q38	0.04	-0.007	15.2	0.214	-0.001	0.221	-0.002	-0.003	1.140	-0.02	17.00	0.06	-0.02	-0.03	0.02	0.03	-0.02	-0.04	-0.05	-0.1	1.7	-0.2
Q62*	-0.03	-0.007	18.2	0.054	-0.001	0.130	-0.002	-0.003	1.290	-0.02	5.14	0.05	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	0.7	-0.2
Q69*	0.05	-0.007	19.3	0.382	-0.001	0.219	-0.002	-0.003	1.990	-0.02	0.05	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q57	0.03	-0.007	15.2	0.195	-0.001	0.248	-0.002	-0.003	0.411	-0.02	0.09	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q56	-0.03	-0.007	9.4	0.466	-0.001	0.447	-0.002	-0.003	1.350	-0.02	-0.02	-0.02	-0.02	-0.03	0.03	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Lower Aquifer System																						
Q37a	-0.03	-0.007	13.7	0.035	-0.001	0.061	-0.002	-0.003	0.075	-0.02	2.34	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	0.11	-0.1	-0.1	-0.2
Q34a	-0.03	-0.007	17.1	0.134	-0.001	0.222	-0.002	-0.003	0.398	-0.02	24.00	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q33a	-0.03	-0.007	20.8	0.052	-0.001	0.078	-0.002	-0.003	0.217	-0.02	6.51	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
G1 HOAI DUC No:7	-0.03	-0.007	17.7	0.282	-0.001	0.589	-0.002	-0.003	0.077	-0.02	11.30	0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
MAI DICH No:5	-0.03	-0.007	19.7	0.129	-0.001	0.029	-0.002	-0.003	0.676	-0.02	0.02	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
324	-0.03	-0.007	16.8	0.132	-0.001	0.073	-0.002	-0.003	0.304	-0.02	4.88	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
PHANG ARMY CAMP	-0.03	-0.007	16.1	0.328	-0.001	0.418	-0.002	-0.003	0.106	-0.02	11.70	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
TAN LAP DAN PHUONG	-0.03	-0.007	9.3	0.657	-0.001	0.526	-0.002	-0.003	0.236	-0.02	7.43	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
DAN HOAI ST. No:38	-0.03	-0.007	19.5	0.126	-0.001	0.126	-0.002	-0.003	0.342	-0.02	18.30	0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
CENTRE FOR VEG.	-0.03	-0.007	19.7	0.063	-0.001	0.068	-0.002	-0.003	0.467	-0.02	5.50	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
MAPPING DIV. No:462	-0.03	-0.007	14.3	0.117	-0.001	0.132	-0.002	-0.003	3.970	-0.02	-0.02	3.30	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	0.08	-0.1	-0.1	-0.2
AGRICULTURAL COLLEGE	-0.03	-0.007	22.1	0.061	-0.001	0.083	-0.002	-0.003	0.448	-0.02	11.20	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
QUANG BA HOTEL No:62	-0.03	-0.007	10.6	0.262	-0.001	0.298	-0.002	-0.003	1.770	-0.02	-0.02	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
YENPHONG - HABAC	-0.03	-0.007	17.9	0.055	-0.001	0.275	-0.002	-0.003	0.924	-0.02	13.30	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
VANHA - DONGANH	-0.03	-0.007	16.8	0.172	-0.001	0.131	-0.002	-0.003	1.960	-0.02	0.12	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q68b	-0.03	-0.007	13.7	0.140	-0.001	0.268	-0.002	-0.003	0.512	-0.02	37.60	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q119b	-0.03	-0.007	16.7	0.091	-0.001	0.205	-0.002	-0.003	0.652	-0.02	7.89	0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q12ob	-0.03	-0.007	22.0	0.068	-0.001	0.138	-0.002	-0.003	0.537	-0.02	13.60	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q127a	0.54	-0.007	15.7	0.693	-0.001	0.098	-0.002	0.013	2.360	-0.02	63.50	0.04	-0.02	-0.03	0.04	-0.02	-0.02	-0.04	0.06	-0.1	1.5	-0.2
Q62a*	-0.03	-0.007	17.6	0.050	-0.001	0.174	-0.002	-0.003	0.377	-0.02	17.80	0.04	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q35	-0.03	-0.007	15.6	0.158	-0.001	0.147	-0.002	-0.003	1.210	-0.02	0.27	0.03	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q36	-0.03	0.013	12.7	0.122	0.002	0.100	0.002	0.017	3.730	0.15	42.90	0.21	-0.02	-0.03	0.03	0.04	-0.02	-0.04	0.18	-0.1	1.1	-0.2
Q67a	-0.03	-0.007	14.3	0.265	-0.001	0.076	-0.002	-0.003	0.937	-0.02	5.75	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q57a	-0.03	-0.007	16.6	0.302	-0.001	0.147	-0.002	-0.003	0.509	-0.02	-0.02	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q173	-0.03	-0.007	16.5	0.317	-0.001	0.199	-0.002	-0.003	0.026	-0.02	-0.02	-0.02	-0.02	-0.03	0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2

Appendix 2: Minor and trace metal data for baseline sites. All data is as mg/l. Negative values indicate the lowest quotable concentration. Sites marked with a * fall within the zone of influence for pumping of well fields.

Urban Sites

Locality	Easting	Northing	Date Sampled	T°C	pH Field.	pH Lab.	Eh mV	DO_2	TOC	SEC μS/cm	HCO_3	Na	K	Ca	Mg	Cl	NO_3	NH_4	SO_4	P_{total}
Upper Aquifer System																				
P14b	1858574	232634	June 1994	27.1	6.76	nd	245	-0.1	nd	nd	299.0	30.7	2.6	38.9	31.2	33.0	8.0	0.82	8.0	-0.5
P14c	1858574	232634	June 1994	27.6	6.96	nd	88	3.6	nd	nd	450.0	39.1	9.4	94.3	19.8	24.2	-1.8	1.95	0.8	-0.5
P10b	1858371	232960	June 1994	27.2	6.00	nd	nd	-0.1	nd	nd	71.3	16.0	2.5	5.9	7.9	19.5	2.7	-0.03	-0.5	-0.5
P25b	1858182	232303	June 1994	28.2	nd	nd	nd	0.3	nd	nd	311.0	12.4	0.9	41.8	9.6	9.5	-1.8	6.17	-0.5	1.4
P42b	1858842	232112	June 1994	nd	6.59	nd	nd	nd	nd	nd	nd	117.0	12.3	182.0	47.9	178.0	-1.8	7.20	38.1	-0.5
Q63	1858121	232764	September 1994	nd	nd	8.0	nd	nd	nd	nd	335.6	40.7	0.5	58.1	18.5	23.9	9.0	nd	2.4	nd
P53b	1858878	232194	September 1994	nd	nd	nd	nd	nd	nd	nd	91.5	57.6	0.8	15.0	12.2	106.4	4.0	nd	1.2	nd
Q65a	1858827	231884	September 1994	nd	nd	7.4	nd	nd	nd	nd	152.6	25.2	1.5	24.1	5.5	28.4	nd	2.91	1.2	nd
Q66	1858824	231518	September 1994	nd	nd	7.3	nd	nd	nd	nd	155.6	17.3	0.5	27.3	11.1	17.7	2.3	nd	9.6	nd
Q68a	1858106	232043	September 1994	nd	nd	7.9	nd	nd	nd	nd	207.5	24.2	0.5	36.1	15.8	19.5	2.6	nd	16.1	nd
LINH NAM THANHI	1859290	232271	February 1995	22.8	7.0	nd	nd	nd	2.2	624	525.0	9.1	1.6	111.0	26.9	7.0	-0.9	8.61	-0.5	-0.5
P34b	1858637	232812	March 1995	nd	nd	nd	nd	nd	nd	nd	517.1	47.9	5.0	98.2	26.8	53.2	0.7	nd	nd	nd
P58b	1858845	232805	March 1995	23.5	7.2	nd	nd	0.5	nd	nd	255.0	19.0	1.7	66.1	10.9	12.4	1.6	nd	12.0	nd
Q64	1858636	232352	March 1995	26.1	6.1	nd	nd	0.3	nd	nd	257.0	39.2	2.1	31.1	11.9	53.2	nd	6.30	1.2	nd
P35b	1858804	232544	March 1995	26.5	6.0	nd	nd	0.4	nd	nd	102.0	59.2	2.2	22.0	19.5	133.8	nd	nd	nd	nd
P38b	1858779	232112	March 1995	26.7	6.2	nd	nd	1.4	nd	nd	528.0	92.5	2.7	104.2	27.4	110.8	nd	9.80	9.6	nd
P45b	1858203	232066	March 1995	26.0	5.9	nd	nd	0.4	nd	nd	278.0	23.2	1.4	43.0	10.0	28.4	nd	5.30	2.4	nd
P41b	1828381	232194	March 1995	25.0	6.2	nd	nd	0.5	nd	nd	307.0	36.8	1.8	47.2	25.5	35.5	nd	nd	2.4	nd
P59b	1858230	232317	March 1995	24.6	6.5	nd	nd	0.7	nd	nd	250.0	19.8	1.1	33.1	11.4	22.2	nd	2.12	0.6	nd
P12b	1858465	232413	March 1995	25.2	6.3	nd	nd	0.6	nd	nd	435.0	43.6	2.7	93.2	21.9	72.7	nd	9.70	9.6	nd
P28c	1858411	231864	March 1995	25.7	6.6	nd	nd	0.9	nd	nd	280.0	25.9	0.9	47.1	12.8	65.6	nd	23.40	7.2	nd
Lower Aquifer System - LAS																				
P14a	1858574	232634	June 1994	27.7	6.34	nd	278	-0.1	nd	nd	181.0	22.0	3.0	18.7	20.1	22.0	-1.8	0.55	6.7	-0.5
P10a	1858371	232960	June 1994	26.7	5.96	nd	178	-0.1	nd	nd	74.4	15.7	2.2	8.2	7.1	19.8	-1.8	-0.03	2.5	-0.5
P25a	1858182	232303	June 1994	28.5	6.39	nd	49	-0.1	nd	nd	243.0	13.8	1.8	28.3	10.9	4.5	-1.8	8.61	-0.5	1.2
P42a	1858842	232112	June 1994	nd	6.60	nd	83	-0.1	nd	nd	307.0	29.7	4.7	27.6	13.4	17.5	-1.8	25.71	-0.5	1.3
YEN PHU No:20	1858764	232829	June 1994	26.5	6.83	nd	97	0.3	nd	nd	272.0	16.9	7.5	48.1	13.1	17.5	-1.8	4.63	3.8	0.9
NGO SI LIEN No:21	1858710	232612	June 1994	27.5	6.53	nd	192	0.2	nd	nd	247.0	40.3	3.8	24.6	30.9	55.0	-1.8	0.60	5.4	-0.5
PHAP VAN No:1	1858792	231964	June 1994	28.0	6.49	nd	92	-0.1	nd	nd	277.0	32.6	4.8	24.2	11.3	13.5	-1.8	20.57	-0.5	1.1

Appendix 3 Major element data for urban sites. All data is as mg/l unless otherwise stated. Negative values indicate the lowest quotable concentration. Parameters not determined are indicated by : nd.

Locality	Easting	Northing	Date Sampled	T°C	pH Field.	pH Lab.	Eh mV	DO_2	TOC	SEC $\mu S/cm$	HCO_3	Na	K	Ca	Mg	Cl	NO_3	NH_4	SO_4	P_{total}
LAS (cont'd)																				
Q63a	1858121	232764	September 1994	nd	nd	7.6	nd	nd	nd	nd	195.3	36.4	0.4	12.0	13.7	9.6	nd	nd	3.6	nd
P53a	1858878	232194	September 1994	nd	nd	7.2	nd	nd	nd	nd	nd	37.1	0.4	20.0	9.9	11.3	3.2	1.20	nd	nd
Q65b	1858827	231884	September 1994	nd	nd	7.5	nd	nd	nd	nd	115.9	24.4	1.3	23.1	4.9	28.4	3.4	nd	3.6	nd
Q66b	1858904	231494	September 1994	nd	nd	7.8	nd	nd	nd	nd	158.7	52.1	1.1	15.0	6.7	39.0	3.4	nd	4.8	nd
MINING and TEC. UNI. 64	1858048	233138	February 1995	26.0	6.4	nd	nd	nd	nd	286	183.0	31.3	2.1	16.8	8.3	3.0	-0.9	0.23	-0.5	-0.5
LUONG YEN PS. No:7	1858950	232441	February 1995	25.7	6.0	nd	157	-0.1	nd	237	139.0	11.5	1.5	21.9	9.6	4.0	8.0	1.54	3.0	0.9
HA DONG PS. No:8	1858100	232030	February 1995	26.4	6.4	nd	108	-0.1	nd	322	187.0	13.9	0.8	32.4	9.6	15.4	-0.9	2.93	-0.5	1.0
HA DINH PS. No:8	1858380	232215	February 1995	26.7	6.4	nd	110	-0.1	nd	496	250.0	27.1	3.0	30.4	17.2	33.8	-0.9	12.47	-0.5	1.2
DON THNY PS. No:7	1858932	232564	February 1995	24.5	6.7	nd	73	-0.1	nd	203	141.0	4.9	1.3	27.7	10.2	2.9	-0.9	-0.03	4.1	1.3
LUONG YEN PS. No:10	1859036	232410	February 1995	26.2	6.7	nd	71	-0.1	nd	227	139.0	3.2	1.4	29.8	8.3	0.9	-0.9	1.07	4.4	0.7
NGO SI LIEN PS. No:21	1858710	232610	February 1995	26.6	6.1	nd	208	-0.1	nd	527	236.0	40.5	3.8	24.5	31.8	50.8	-0.9	0.60	5.3	-0.5
YEN PHU PS. No:17	1858790	232874	February 1995	24.9	6.8	nd	77	-0.1	1.1	216	169.0	3.5	1.4	36.2	9.3	1.4	-0.9	1.76	2.7	-0.5
PETROL INST. No:126	1858312	232480	February 1995	23.9	6.3	nd	nd	nd	nd	304	203.0	20.6	2.1	23.6	12.2	14.2	-0.9	0.98	-0.5	0.8
NGOC HA PS. No:7	1858440	232787	February 1995	25.5	6.4	nd	119	0.1	1.3	319	172.0	18.2	4.2	25.1	17.1	26.8	-0.9	1.80	3.8	-0.5
MEDICAL UNIVERSITY	1858640	232376	February 1995	25.6	6.4	nd	4	-0.1	3.4	470	288.0	28.9	1.5	40.4	16.1	39.2	-0.9	9.64	-0.5	1.0
BACHMAI PS.	1858645	232326	February 1995	26.0	6.4	nd	35	0.9	3.0	446	274.0	31.6	2.7	31.5	15.4	33.6	-0.9	13.37	-0.5	1.0
MECHANICAL FACTORY	1858474	232352	February 1995	25.9	6.5	nd	48	-0.1	2.6	493	259.0	29.0	1.6	48.0	17.2	52.8	-0.9	9.39	-0.5	1.2
FACTORY No: 43A	1858391	232846	February 1995	25.0	7.6	nd	47	-0.1	1.2	362	209.0	14.2	2.5	29.0	23.3	28.3	-0.9	0.06	-0.5	-0.5
P30a	1858426	232770	March 1995	25.6	6.1	nd	nd	1.2	nd	nd	264.0	18.2	2.5	47.1	40.1	23.0	nd	nd	12.0	nd
P58a	1858845	232805	March 1995	23.8	7.4	nd	nd	0.6	nd	nd	126.0	7.0	1.5	39.8	5.8	7.1	1.6	nd	6.6	nd
P34a	1858637	232812	March 1995	24.5	6.7	nd	nd	0.6	nd	nd	366.0	18.8	1.7	68.1	28.6	35.5	17.1	nd	4.8	nd
P38a	1858779	232412	March 1995	25.6	5.9	nd	nd	0.3	nd	nd	290.0	37.9	1.6	30.1	20.4	32.8	19.8	nd	nd	nd
Q64a	1858636	232352	March 1995	26.5	nd	nd	nd	0.3	nd	nd	288.0	37.4	3.7	37.1	13.7	39.0	0.3	4.40	nd	nd
P45a	1858203	232066	March 1995	26.5	6.6	nd	nd	0.7	nd	nd	247.0	22.7	1.5	38.8	10.9	26.6	nd	4.50	nd	nd
P8a	1858363	232503	March 1995	nd	nd	nd	nd	nd	nd	nd	378.0	48.4	2.5	70.1	37.7	86.9	nd	1.60	16.8	nd
P59a	1858230	232317	March 1995	25.5	6.2	nd	nd	0.7	nd	nd	322.0	33.0	1.9	50.1	15.2	17.7	nd	16.00	43.2	nd
P12a	1858465	232413	March 1995	25.4	6.3	nd	nd	0.6	nd	nd	316.0	44.3	3.0	63.1	17.6	65.6	nd	5.30	14.4	nd
P28a	1858411	231864	March 1995	26.0	6.0	nd	nd	1.2	nd	nd	330.0	31.9	1.4	44.1	14.6	46.1	nd	21.20	4.8	nd
Neogene																				
P48N	1858594	232155	June 1994	24.7	7.81	nd	217	7.8	nd	nd	496.0	45.7	4.6	65.7	19.7	38.5	-1.8	46.29	-0.5	-0.5

Urban Sites

LOCALITY	B	Li	Si	Sr	Be	Ba	Sc	Y	Mn	Co	Fe_{total}	Zn	V	Cd	La	Cu	Zr	Cr	Ni	Mo	Al	Pb
Upper Aquifer System																						
P14b	-0.03	-0.007	15.4	0.22	-0.001	0.172	-0.002	-0.003	2.98	-0.02	0.2	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	0.07	-0.1	-0.1	-0.2
P14c	0.04	-0.007	16.6	0.32	-0.001	0.09	-0.002	-0.003	1.66	-0.02	1.21	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	0.1	-0.1	-0.2
P10b	-0.03	-0.007	19.6	0.1	-0.001	0.106	-0.002	-0.003	0.152	-0.02	0.63	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	0.05	-0.1	0.3	-0.2
P25b	-0.03	-0.007	26	0.12	-0.001	0.419	-0.002	-0.003	1.28	-0.02	50	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	0.06	-0.1	-0.1	-0.2
P42b	0.08	0.008	15.1	0.8	-0.001	0.373	-0.002	-0.003	3.22	-0.02	10.3	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	0.08	-0.1	-0.1	-0.2
Q63	nd	nd	12.3	nd	nd	nd	nd	nd	0.17	nd	7.13	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Q66	nd	nd	4.1	nd	nd	nd	nd	nd	0.049	nd	19.44	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.1	nd
Q65a	nd	nd	3.3	nd	nd	nd	nd	nd	0.082	nd	10.99	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.1	nd
P53b	nd	nd	nd	nd	nd	nd	nd	nd	0.049	nd	1.8	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.1	nd
Q68a	nd	nd	2.7	nd	nd	nd	nd	nd	0.065	nd	10.82	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
LINH NAM THANHI	-0.03	-0.007	13.6	0.26	-0.001	0.544	-0.002	-0.003	0.087	-0.02	13.9	0.03	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
P34b	nd	nd	8.2	nd	nd	nd	nd	nd	0.47	nd	55.84	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P58b	nd	nd	5.6	nd	nd	nd	nd	nd	0.76	nd	0.35	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Q64	nd	nd	12.7	nd	nd	nd	nd	nd	0.3	nd	28.97	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P35b	nd	nd	11.7	nd	nd	nd	nd	nd	3.04	nd	17.11	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P38b	nd	nd	14.7	nd	nd	nd	nd	nd	0.43	nd	23.04	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P45b	nd	nd	10.1	nd	nd	nd	nd	nd	0.57	nd	20.25	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P41b	nd	nd	10.1	nd	nd	nd	nd	nd	0.43	nd	11.17	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P59b	nd	nd	12.1	nd	nd	nd	nd	nd	0.2	nd	30.72	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P12b	nd	nd	14.2	nd	nd	nd	nd	nd	0.57	nd	18.5	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P28c	nd	nd	13	nd	nd	nd	nd	nd	0.18	nd	13.96	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Lower Aquifer System - LAS																						
P14a	-0.03	0.01	19.4	0.2	-0.001	0.028	-0.002	-0.003	0.456	-0.02	0.16	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
P10a	-0.03	0.008	22.4	0.1	-0.001	0.052	-0.002	-0.003	0.293	-0.02	0.44	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
P25a	-0.03	-0.007	22.4	0.17	-0.001	0.091	-0.002	-0.003	0.321	-0.02	22.1	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
P42a	-0.03	-0.007	19.9	0.17	-0.001	0.26	-0.002	-0.003	0.137	-0.02	10.6	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
YEN PHU No:20	-0.03	-0.007	14.9	0.19	-0.001	0.289	-0.002	-0.003	0.382	-0.02	9.42	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
NGO SI LIEN No:21	-0.03	-0.007	15.4	0.27	-0.001	0.102	-0.002	-0.003	0.893	-0.02	1.64	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
PHAP VAN No:1	-0.03	-0.007	19.4	0.15	-0.001	0.231	-0.002	-0.003	0.107	-0.02	7.73	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
Q63a	nd	nd	14	nd	nd	nd	nd	nd	0.216	nd	6.3	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P53a	nd	nd	12.5	nd	nd	nd	nd	nd	0.082	nd	14.12	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Q65b	nd	nd	3.3	nd	nd	nd	nd	nd	0.07	nd	21.34	nd	nd	nd	nd	nd	nd	nd	nd	nd	0.1	nd
Q66b	nd	nd	4.5	nd	nd	nd	nd	nd	0.12	nd	12.82	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
MINING and TEC. UNI. 64	-0.03	0.007	23.9	0.12	-0.001	0.08	-0.002	-0.003	0.261	-0.02	7.59	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2

Appendix 4 Minor and trace metal element data for urban sites. All data is as mg/l unless otherwise stated. Negative values indicate the lowest quotable concentration. Parameters not determined are indicated by: nd

LOCALITY	B	Li	Si	Sr	Be	Ba	Sc	Y	Mn	Co	Fe_{total}	Zn	V	Cd	La	Cu	Zr	Cr	Ni	Mo	Al	Pb
LAS (cont'd)																						
LUONG YEN PS. No:7	-0.03	-0.007	16.5	0.11	-0.001	0.05	-0.002	-0.003	0.393	-0.02	3.73	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
HA DONG PS. No:8	-0.03	-0.007	20.1	0.1	-0.001	0.147	-0.002	-0.003	0.199	-0.02	12.7	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
HA DINH PS. No:8	-0.03	-0.007	18.6	0.22	-0.001	0.195	-0.002	-0.003	0.137	-0.02	18.6	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
DON THNY PS. No:7	-0.03	-0.007	11.2	0.13	-0.001	0.068	-0.002	-0.003	0.112	-0.02	3.27	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
LUONG YEN PS. No:10	-0.03	-0.007	8.1	0.13	-0.001	0.034	-0.002	-0.003	0.242	-0.02	1.62	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
NGO SI LIEN PS. No:21	-0.03	-0.007	14.7	0.27	-0.001	0.101	-0.002	-0.003	0.947	-0.02	1.61	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
YEN PHU PS. No:17	-0.03	-0.007	10.6	0.15	-0.001	0.048	-0.002	-0.003	0.411	-0.02	0.66	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
PETROL INST. No:126	-0.03	-0.007	22.8	0.19	-0.001	0.09	-0.002	-0.003	1.22	-0.02	15.3	0.13	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
NGOC HA PS. No:7	-0.03	-0.007	15.7	0.21	-0.001	0.071	-0.002	-0.003	0.606	-0.02	1	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
MEDICAL UNIVERSITY	-0.03	-0.007	18.5	0.16	-0.001	0.291	-0.002	-0.003	0.52	-0.02	24.1	0.04	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
BACHMAI PS.	-0.03	-0.007	20.1	0.19	-0.001	0.186	-0.002	-0.003	0.27	-0.02	14.8	0.31	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
MECHANICAL FACTORY	-0.03	-0.007	20.5	0.23	-0.001	0.126	-0.002	-0.003	0.239	-0.02	10.3	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
FACTORY No:43A	-0.03	-0.007	13.8	0.3	-0.001	0.121	-0.002	-0.003	1.87	-0.02	7.25	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
P30a	nd	nd	8.5	nd	nd	nd	nd	nd	2.86	nd	23.04	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P58a	nd	nd	5.1	nd	nd	nd	nd	nd	0.22	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P34a	nd	nd	10.3	nd	nd	nd	nd	nd	0.22	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P38a	nd	nd	11.4	nd	nd	nd	nd	nd	0.35	nd	11.87	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Q64a	nd	nd	16.1	nd	nd	nd	nd	nd	0.73	nd	19.55	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P45a	nd	nd	9.3	nd	nd	nd	nd	nd	0.22	nd	17.36	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P8a	nd	nd	11.7	nd	nd	nd	nd	nd	1	nd	17.46	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P59a	nd	nd	11.8	nd	nd	nd	nd	nd	0.18	nd	16.76	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P12a	nd	nd	16.8	nd	nd	nd	nd	nd	0.6	nd	15.71	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
P28a	nd	nd	18.2	nd	nd	nd	nd	nd	0.22	nd	9.08	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Neogene																						
P48N	0.11	0.01	15.9	0.33	-0.001	0.212	-0.002	-0.003	0.442	-0.02	3.3	-0.02	-0.02	-0.03	0.03	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2

Surface Waters, Rainwater and Acid Blank

LOCALITY	Easting	Northing	Date Sampled	T°C	Ph Field	DO_2	SEC µS/cm	HCO_3	Na	K	Ca	Mg	Cl	NO_3	NH_4	SO_4	P_{total}
ACID BLANK	-	-	June 1994	nd	nd	nd	nd	nd	-0.05	-0.5	-0.1	-0.1	nd	nd	nd	-0.5	-0.5
RAIN WATER	-	-	June 1994	nd	nd	nd	nd	nd	nd	nd	nd	nd	-0.5	-1.8	0.26	nd	nd
RED RIVER	1858949	232694	June 1994	26.0	6.9	7.8	nd	93.9	2.7	1.4	23.5	4.1	0.5	2.2	-0.03	5.0	-0.5
NHUE RIVER	1858110	232055	June 1994	31.0	7.3	nd	nd	98.1	7.5	4.8	23.5	4.7	9.0	4.9	-0.03	7.6	-0.5
TO LICH RIVER	1858330	232665	June 1994	31.0	7.2	nd	nd	122	19.4	7.9	24.7	7.6	25.0	12.4	-0.03	15.2	-0.5
RED RIVER	1858088	233383	Feb. 1995	17.3	6.5	5.6	176	98.7	3.5	1.3	26.1	5.4	1.6	1.3	-0.03	6.3	-0.5
WEST LAKE	1858424	233065	Feb. 1995	17.0	6.5	5.7	234	61.5	24.0	7.2	6.8	8.3	26.8	4.9	-0.03	17.3	-0.5
LU RIVER	1858684	232317	Feb. 1995	20.9	7.0	-0.1	739	322	147	12.5	37.1	18.1	52.8	116	-0.03	14.8	1.7
TO LICH RIVER	1858457	232250	Feb. 1995	18.8	6.9	1.7	395	153	30.3	6.8	25.1	11.1	31.6	27.0	-0.03	22.7	-0.5
WEST LAKE	1858510	233000	March 1995	14.5	7.2	0.3	nd	78.0	29.2	1.1	34.1	10.9	35.5	17.5	nd	14.4	nd
TO LICH RIVER	1858410	231850	March 1995	19.0	7.1	4.8	nd	293	50.7	4.9	46.1	14.6	58.5	2.6	16.2	9.6	nd
ME TRI LAKE	1858210	232290	March 1995	19.4	7.8	6.7	nd	196.0	39.7	1.6	36.6	12.3	47.9	15.9	nd	4.2	nd

LOCALITY	B	Li	Si	Sr	Be	Ba	Sc	Y	Mn	Co	Fe_{total}	Zn	V	Cd	La	Cu	Zr	Cr	Ni	Mo	Al	Pb
ACID BLANK	-0.03	-0.007	-0.1	-0.001	-0.001	-0.003	-0.002	-0.003	-0.003	-0.02	-0.02	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
RAIN WATER	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
RED RIVER	-0.03	-0.007	4.4	0.083	-0.001	0.036	-0.002	-0.003	0.012	-0.02	0.06	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
SONG NHUE	-0.03	-0.007	4.0	0.076	-0.001	0.041	-0.002	-0.003	0.023	-0.02	0.09	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
SONG TO LICH	-0.03	-0.007	6.3	0.097	-0.001	0.048	-0.002	-0.003	0.138	-0.02	0.26	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
RED RIVER	-0.03	-0.007	4.6	0.088	-0.001	0.027	-0.002	-0.003	0.007	-0.02	0.06	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	0.3	-0.2
WEST LAKE	0.04	-0.007	4.4	0.049	-0.001	0.039	-0.002	-0.003	0.006	-0.02	0.09	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
LU RIVER	0.08	-0.007	15.1	0.203	-0.001	0.078	-0.002	-0.003	0.524	-0.02	0.51	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	0.10	-0.1	-0.1	-0.2
TO LICH RIVER	0.03	-0.007	6.7	0.124	-0.001	0.043	-0.002	-0.003	0.151	-0.02	0.15	-0.02	-0.02	-0.03	-0.02	-0.02	-0.02	-0.04	-0.05	-0.1	-0.1	-0.2
WEST LAKE	nd	nd	3.7	nd	nd	nd	nd	nd	0.130	nd	1.05	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
TO LICH RIVER	nd	nd	12.7	nd	nd	nd	nd	nd	0.260	nd	1.75	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
ME TRI LAKE	nd	nd	2.3	nd	nd	nd	nd	nd	nd	nd	0.70	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Appendix 5 Data for surface waters. All data is as mg/l unless otherwise stated. Negative values indicate the lowest quotable concentration. Parameters not determined are indicated by : nd.

Locality	$\delta^{18}O$ ‰	$\delta^{2}H$ ‰	$\delta^{13}C_{DIC}$ ‰	**TOC** mg/l
Surface Waters				
Red River	-8.3	-45	nd	nd
Lu River	-7.3	-48	nd	nd
To Lich River	-4.3	-31	nd	nd
Red River	-10.4	-51	nd	nd
West Lake	-5.9	-35	nd	nd
Nhue River	-9.7	-64	nd	nd
To Lich River	-14.8	-60	nd	nd
Top Aquifer (Qiv)				
Lin Nam Thani	-7	-48	-17.1	2.2
P10b	-9.3	-47	nd	nd
P14c	-7.1	-51	nd	nd
P12b	-6.9	-42	nd	nd
P53b	-8.8	-62	nd	nd
P42b	-7.2	-52	nd	nd
P44b	-4.3	-31	nd	nd
P47b	-9	-63	-8.8	nd
Q68A	-11.9	-65	nd	nd
P59b	-5.9	-34	nd	nd
Main Aquifer (Qii.iii)				
Centre for Protection Veg.	nd	nd	-18.3	0.8
Mapping Division No: 462	nd	nd	nd	2.0
Agricultural College	nd	nd	-21.1	0.7
Floor Tile Factory No: 43a	nd	nd	-14.1	1.2
Mechanical Equipment Factory	nd	nd	-16.2	2.6
Phang Army Camp	-7.7	-32	-14.3	1.7
Tan Lap Dan Phong	-8.5	-53	-16.4	6.5
Dan Hoai PS No:38	-5.8	-37	-13.9	2.4
Mining and Technical University	-7.4	-51	nd	nd
Yen Phu PS No: 17	-8.8	-56	-16.2	1.1
Medical University	-5.8	-36	-10.6	3.4
Bach Mai PS	-6.3	-44	-12.7	3.0
Q37A	-6.3	-47	nd	nd
Q34A	-5.5	-48	nd	nd
G1 Hoai Duc	-5.4	-42	nd	nd
P10a	-10.1	-56	nd	nd
P14a	-6.9	-46	nd	nd
P12a	-6.2	-43	nd	nd
P53a	-8.2	-52	nd	nd
P42a	-7.8	-50	nd	nd
P44a	-5	-36	nd	nd
P47a	-8.9	-61	nd	nd
Q66B	-7.4	-50	nd	nd
Ngo Si Lien No:21	-8.9	-55	nd	nd
Mai Dich No:5	-7.4	-48	nd	nd
Lung Yen No:7	-8.8	-57	nd	nd
P59a	-5.1	-38	nd	nd
Neogene				
P48N	-6.9	-46	nd	nd
P10N	-8.5	-44	nd	nd
P44N	-4.6	-33	nd	nd

Appendix 6: Stable isotope and total organic carbon (TOC) data. nd= not determined