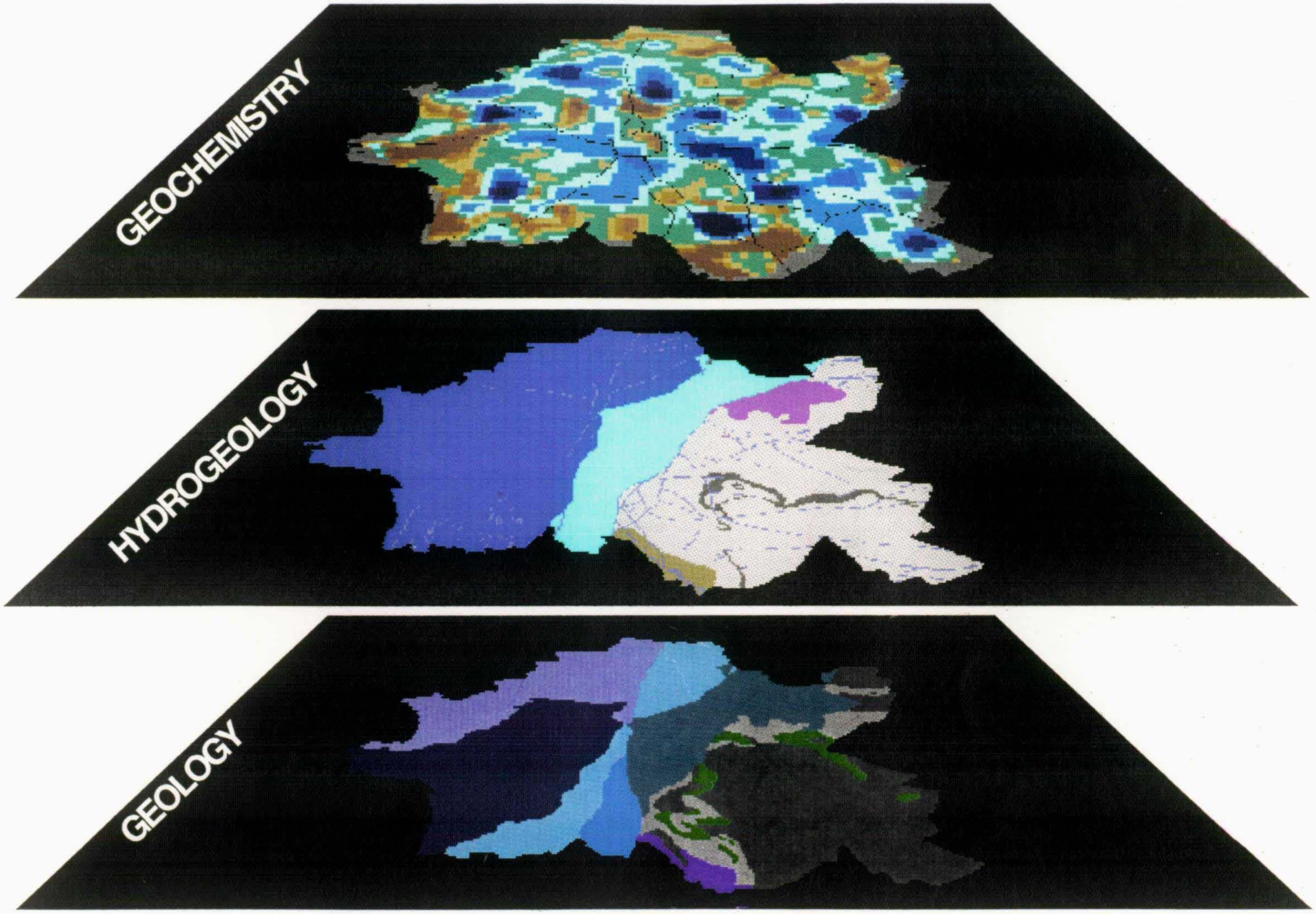
INTEGRATED URBAN ENVIRONMENTAL SURVEY OF WOLVERHAMPTON



British Geological Survey

Natural Environment Research Council

WOLVERHAMPTON URBAN ENVIRONMENTAL SURVEY

An integrated geoscientific case study

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Foreword

This report represents a summary of the creation and compilation of key geoscientific datasets relevant to an integrated multidisciplinary pilot survey of the urban environment in the Metropolitan Borough of Wolverhampton, West Midlands, England. The work presented here has been carried out by the British Geological Survey over a period of three years from April 1993. Different geoscientific datasets housed in various digital environments have been drawn together and incorporated within a new user-friendly PC-based Geographical Information System (GIS).

Using commercially available software, geoscience data from selected GIS layers can be manipulated and interpreted to produce new composite maps showing, for example, geohazards for engineering work or hazards associated with soil quality. This GIS provides a powerful tool for making interpretations of the geoscientific and land use information in terms of risk assessment. The purpose of this report, however, is not to demonstrate this application of the GIS but rather to describe the contents of the different datasets embodied therein. For convenience in presentation, the diagrams and figures in this report have been generated at a scale of 1:50 000 but, using the GIS capability, they could equally well be combined into multilayer maps at much larger scales.

Executive Summary

Geoscience and land use information for the Metropolitan Borough of Wolverhampton have been collated, with the assistance of the Metropolitan Authority, and interpreted with the aid of a Geographical Information System (GIS). The digital data can be rapidly manipulated within the GIS to produce customised thematic maps of the urban area.

The report is a summary of a study undertaken in the Borough over a period of three years, and is supported by a number of satellite reports which describe in more detail different aspects of the work.

The Borough of Wolverhampton lies on the western edge of the South Staffordshire Coalfield. The Western Boundary Fault bisects the Borough and marks the edge of the exposed coalfield. To the west of this structure the Coal Measures are concealed by a thick sequence of Upper Carboniferous and Permo-Triassic redbeds. Glacial deposits, mainly clay-rich till with subordinate sands, gravels and laminated clays, cover much of the area. The till is of variable thickness but due to its impermeability it affords some protection to the migration of potential contaminants. Spoil and waste (made ground) from former coal workings cover much of the eastern part of the Borough which is also extensively undermined. Thematic maps indicating the extent and depth of the made ground, depth of till, extent of undermining and location of landfill sites provide useful planning information.

The Triassic sandstone is an important aquifer in terms of its water-bearing characteristics and in the quantity of water pumped for supply. Abstraction from the aquifer has decreased as industrial demand has declined, resulting in a rise of the water table. Despite a shortage of hydrogeological data, some indication is given of the extent of the rising groundwater levels from borehole information. In some areas this may cause localised flooding and potentially cause the remobilisation and migration of contaminants. Borehole waters across the Borough have been analysed at several sites, and results show the presence of trace amounts of chlorinated hydrocarbon compounds which were used in the metal finishing industry. Data have been assessed to provide an aquifer vulnerability map for the Borough.

Soils were collected at a density of 4 samples per km^2 throughout the urban area, and at a density of 25 samples per km^2 in south-west Wolverhampton, to test optimum sampling strategies. Geochemical maps of the Borough give a broad indication of the distribution of a range of heavy metals and toxic elements (including Cu, Pb, Zn, As and Cd) in both surface (-2mm fraction) and sub-surface (-150μm fraction) soils. However, more detailed sampling would be required to assess particular sites in detail. The distribution of these Potentially Harmful Elements (PHEs) in soil can, in most cases, be related to land use, particularly past and present industrialisation and atmospheric input. A comparison of urban soil data with soil data from the surrounding rural area indicates a marked change in the background levels of PHEs within the built environment. This is common to most urban centres.

Two case studies are summarised in the report: one centred on Bowmans Harbour, the other at East Park. In the former, redevelopment of a 1960s landfill site has enabled leachate studies to be carried out in two sections where landfill and colliery spoil overlie till. Results show that the migration of contaminants into the till is dependent on many factors but penetration rarely exceeds one metre.

East Park, the subject of the second study, was founded in the 1890s on made ground, consisting of colliery spoil and blast furnace waste. The slag-rich horizons show some elevated concentrations of heavy metals but there is little evidence of significant migration due to retention in the source horizons, and the presence of an impermeable till layer below.

The current study has provided a framework for the collection, interpretation and presentation of geoscience data for urban areas. The data have applications to a variety of potential users including planners, developers, local authorities and those concerned with environmental health.

CONTENTS

1. INTRODUCTION

1.1 Background

Public concern over contamination of the built environment has grown rapidly in recent years as the potential health hazards of past and present industrialisation, water pollution and vehicular emissions have become recognised. Under the Environmental Protection Act 1990 and the Environment Act 1995, there will be a requirement for each local authority to inspect its area for contaminated land. Structured planning strategies within built areas are required to make best use of available land and resources for new development. This will include land with a variety of past uses including heavy industry, mining, oil refineries, gasworks, chemical industries, railways and landfill sites.

Where contamination has been caused by former industrial or mining activity, it is important to assess the health and environmental impacts which can arise, and to ensure future problems are not created as a result of current activities.

Although the British Geological Survey has been involved for more than a decade in providing earth science information through urban mapping programmes, the problems of urban contamination have received scant attention. Recognising the need for further research in this area, a pilot study was initiated in 1993 to carry out an integrated geoscience study of the Metropolitan Borough of Wolverhampton. The Borough was selected for the pilot study as it is an area where past industry and mining activities have substantially altered the landscape and left a legacy of derelict and, in part, potentially contaminated ground.

The main objectives of the pilot study were set as follows:

- To integrate geological, geochemical and hydrogeological data for the Borough within a Geographical Information System (GIS)
- To investigate the distribution of selected potentially harmful elements (PHEs) in soils, sediments and groundwater throughout the Borough
- To rank the potential hazards and assess the vulnerability of the aquifers to pollution
- To make a preliminary assessment of the pathways and processes by which contaminants may enter the groundwater and the urban life-cycle

1.2 Methodology

The survey has involved several activities:

- remote sensing survey of made and contaminated land
- geological mapping and rock/sediment characterisation
- geochemical survey of soils, surface waters and canal sediments
- soil gas survey (including radon)
- hydrogeological survey including a sampling campaign from deep boreholes
- local site studies including:
  - leachate transfer through till (Bowmans Harbour)
  - hydrogeology of colliery spoil (East Park)

Data from the above programmes are being assessed with the aid of a GIS and various stand-alone modelling packages. Further development of the GIS is continuing, using a PC-based system as a demonstration platform.

The results of the work are presented as an atlas of maps and diagrams, each supported by a short explanation. Except where noted otherwise, the maps have been generated at a scale of 1:50 000 to reduce bulk. Larger scale maps with a full topographic backdrop can be generated on demand. The report is divided into three main sections; the first sets out the geological framework, the second deals with the results of the geochemical surveys, and the third is devoted to hydrogeology. The report also includes sections on airborne remote sensing and historical land use. An example of the way in which related datasets can be combined to provide information for the non-specialist is given in a foundations conditions summary map (Figure 42).

1.3 Potential users of the information

The integrated study provides geoscience information at the strategic planning level, and is intended for use by planners, developers, and the banking and insurance sector.

It should be stressed that the information contained in this report should be used for preliminary studies only and is no substitute for on-site investigations or detailed local searches.

1.4 The project area

[Figures 1, 2]

The Metropolitan Borough of Wolverhampton covers an area of 70 square kilometres in the north-west corner of the West Midlands conurbation. The area is one of undulating relief, ranging mainly between 100 and 150 m above OD. Bushbury Hill, Colton Hill and the Tettenhall escarpment are prominent features formed by outcrops of Triassic sandstone. Cinder Hill, in the south of the district, is composed of Silurian rocks, and is the highest point at 200 m above OD.

The Borough lies astride the Severn-Trent watershed and is drained by three principal streams; Smestow Brook and its tributaries drain via the Stour into the Severn, while the Penk and the Tame and their tributaries drain into the Trent. Apart from Smestow Brook, the streams are largely culverted. The Borough is also served by a network of canals, totalling approximately 21 kilometres in length.

The rapid growth of the Borough dates from the Industrial Revolution, when heavy industries were established founded on readily available raw materials, notably coal, ironstone, limestone and fireclay. The development of canal and rail links, and the construction in more recent times of the Midlands motorway links, has contributed to the continued growth of the area, though the emphasis nowadays is shifting away from heavy industry towards light industry, new high technology manufacturing and warehouse-type service industries.

2. AIRBORNE REMOTE SENSING

[Figure 3]

2.1 Background

To assess the contribution remotely sensed data can make to airborne environmental mapping, Daedalus Airborne Thematic Mapper (ATM) data were acquired over Wolverhampton Metropolitan Borough on the 11 April 1994. This acquisition formed part of the NERC Airborne Remote Sensing Campaign 1994/95. Eight flight lines of ATM data were recorded and near complete coverage of the Borough was achieved by combining five of these. Each ATM flight line records data in eleven bands centred on different wavelengths; five measure visible light; three are in the near infrared; two are shortwave infrared bands; and the eleventh band measures energy emitted by the Earth's surface in the thermal infrared wavelength region. The data have 5m pixels, meaning that they can be usefully studied at scales up to 1:10 000.

2.2 Aims of the remote sensing study

It was anticipated that several of the overall project objectives would be more effectively addressed if airborne scanner imagery supplemented conventional approaches. The specific aims of the remote sensing analysis were therefore:

1. To help map superficial deposits
2. To identify areas of made ground or landfill
3. To attempt to identify potentially contaminated sites
4. To provide geological and land-use information for use within the GIS.

Initial data analysis suggested that aim 1 could not be achieved due to the predominance of pasture and urban landcover. To date, work has concentrated on aims 2, 3 and 4.

2.3 Work undertaken in 1994/95

Most of the effort has gone into preparing a standard image product for analysis in combination with other datasets within the GIS. A series of band combinations and image enhancements were examined for the data over Bowmans Harbour opencast site, including natural and false colour composites, band ratios and principal component (PC) images. This showed the most useful band combination to be 11-7-1 in red-green-blue, which combines one band of data from each of the thermal infrared, shortwave infrared and visible wavelength regions. The most informative image enhancement was found to be principal component analysis, a statistical transformation which presents the total variation of all 11 bands in a small number of uncorrelated PC images. Each of these typically depicts a particular landscape variable; for example, PC1 shows the topography, whilst PC3 picks out known opencast sites.

As PC images can be difficult to interpret, the 11-7-1 false colour composite was chosen as the first image product. It not only contains useful spectral information but also clearly depicts roads, railways and buildings. Each flight line was then radiometrically corrected before being registered to the British National Grid using the digital topographic base map. Finally, all five flight lines were `stitched' together to form one large image for bands 11-7-1.

2.4 Initial interpretation

Figure 3 shows the band 11-7-1 composite for the whole of the Borough with an inset at a larger scale of Bowmans Harbour opencast site. Each landcover type has a distinct spectral response in this image: buildings appear red because they are loosing heat through their roofs, giving high band 11 values; healthy vegetation has high reflectance in the near infrared around band 7 and is thus seen in green; and bare soil, rock or concrete have higher reflectance in the visible wavelengths so high values in band 1 render them blue. The opencast site stands out because of a combination of bare ground, distinctive geomorphology and increased values in the thermal band which are as yet unexplained. Analysis of this band combination also shows that landfill sites and other derelict ground have a distinct spectral response which may relate to the invasion of a particular plant species during revegetation. Even where a site has been revegetated for some time, the spectral response is not that of normal healthy vegetation. This may present a way of mapping the extent of contaminated sites where they have not yet been built on.

2.5 Further work

Further analysis of the data will include the calculation of principal components for the merged data set. Past work (Haynes et al., 1981; Jones, 1991) suggests that leachate and gases from landfill sites may cause colour anomalies in soils, areas of damp ground detectable in thermal images, and vegetation stress resulting in barren ground or thinned vegetation cover. The spectral signatures in PC images of sites known to be contaminated will be examined in order to detect any unrecorded `hotspots'.

3. GEOLOGY

3.1 Geological setting

[Figure 4]

The Borough of Wolverhampton lies on the western edge of the South Staffordshire Coalfield. The Western Boundary Fault, with a downthrow to the west of about 900m, bisects the Borough, and marks the edge of the exposed coalfield. To the west of this structure, the Productive Coal Measures are concealed by a thick sequence of Upper Carboniferous and Permo-Triassic red-beds. This sequence includes important aquifers, which are developed more fully towards the centre of the Stafford Basin further to the north-west. The basement consists of Palaeozoic mudstones and limestones, mainly of Silurian age, but is largely concealed except for a small outcrop in the Cinder Hill district.

Glacial deposits of Late Devensian age cover about 75 per cent of the metropolitan area, leaving only the higher ground in the south and west essentially drift-free. The deposits consist of a widespread till sheet with subordinate sands, gravels, and laminated clays.

Spoil from former mineral workings covers much of the eastern part of the Borough, and in the heavily industrialised areas, there is commonly a mixture of fill types. Most are inert but a small proportion may produce hazardous toxic leachates or gases, such as potentially explosive methane.

3.2 Survey and borehole information

[Figure 5]

The Borough of Wolverhampton was surveyed geologically between 1978 and 1993, and is included in parts of eight 1:10 000 geological sheets. Map face data has been captured digitally, and fully attributed in a manner that allows selected geological elements to be displayed as single or multi-element themes. This has the advantage that customised maps can be generated semi-automatically, and at any scale.

The geological compilation is based, in large part, on borehole, shaft and trial pit data acquired from a variety of sources including local authorities, site investigation companies and geotechnical consultants. Currently, the holding for the Wolverhampton area comprises some 6740 records.

A subset of 1900 records, chosen for their stratigraphical reliability, has been digitally encoded, and loaded to an Oracle database. These data can be retrieved and manipulated outside the GIS environment, and form the main input to the `Earthvision' surface modelling package.

Reports containing geological details for the southern parts of the Borough are listed below.

Sheet no.	Name	Report No.	Author
SO89NE	Penn	WA/91/76	Powell, JH
SO99NW	Wolverhampton	WA/91/77	Hamblin, RJO and Powell, JH
SO99NE	Willenhall and Darlaston	WA/91/78	Hamblin, RJO, Henson MR, and Powell, JH
SO99SW	Dudley and Sedgley	WA/91/72	Hamblin, RJO and Glover, BW
SO99SE	Dudley and Wednesbury	WA/91/73	Hamblin, RJO and Glover, BW
SJ90SE	Essington and Bloxwich	-	Hamblin, RJO

More general information is given in a report prepared for the Department of the Environment by Powell et al. (1992).

3.3 Solid (bedrock) geology

[Figures 6-8]

The solid geology of the area is illustrated in Figure 6, generalised cross-sections are given in Figure 7, and representative borehole sections in Figure 8.

Silurian and Devonian

Rocks ranging from Silurian to Early Devonian in age underlie the whole of the area at depth but are only brought to the surface in a folded and faulted inlier that lies mainly outside the Borough boundary. Outcrops of shale interbedded with hard limestone (Plate 1a) form the prominent north-north-west trending ridge that includes Park Hill, Cinder Hill and Hurst Hill. The exposed succession, about 265 m thick, is divided into five formations (Table 1).

Table 1. Silurian stratigraphy.

Formation		Thickness (m)	Lithology
Whitcliffe Formation		12	Flaggy silty shales and thin sandstones, exposed between Cinder Hill and Park Hill
Aymestry Limestone		10	Nodular limestone with greenish grey shaly mudstone, exposed in a northward-plunging anticline on Park Hill
Elton Formation		150	Greenish grey, buff-weathering shales and sandy mudstones with thin beds of limestone nodules, exposed on Hurst Hill
Much Wenlock Limestone Formation	Upper Quarried Limestone	7.3	Hard, shelly limestones containing unbedded, richly fossiliferous patch reef deposits; exploited in quarries and underground workings on Hurst Hill
	Nodular Limestone	31	Nodular shelly limestone interbedded with thin partings of grey-green calcareous mudstone and siltstone
	Lower Quarried Limestone	12.8	As for Upper Quarried Limestone
Coalbrookdale Fm.		40	Monotonous greyish green shales with thin, nodular limestone beds preserved in the core of the Silurian fold at Hurst Hill

Carboniferous

Productive Coal Measures

The Productive Coal Measures have a maximum thickness of about 320 m in the north-east of the Borough (north of the Bentley Trough faults) but reduce to about 190 m beneath central Wolverhampton. In the concealed coalfield around Penn, the sequence is further condensed to around 100 m with only the lower part preserved beneath the sub-Halesowen unconformity.

The Coal Measures consist of sequences of grey mudstone, sandstone, seatearth and coal, with occasional nodular and sphaerosideritic ironstone beds (Figure 8, Plate 1b). Coal seams comprise only a small part of the total thickness (13-17%). The principal named seams are shown on Map 6. As the sequence is traced southwards across the Bentley Faults, the number of seams reduces; the Shallow and Deep coals join to form the Bottom Coal, the Cinder Coal becomes the Fireclay Coal, and the Wyrley Bottom and Old Park join to become the Thick Coal. The principal sandstone units occur at three horizons; at the base of the sequence, above the New Mine Coal (New Mine Coal Rock) and above the Thick Coal (Thick Coal Rock). Of these, the New Mine Coal Rock is the most widely mapped, varying between 12 and 30 m in thickness; it includes siltstone and sandy mudstone lithologies and is commonly coarse-grained and often pebbly at the base.

Intrusive **dolerites** associated with the Coal Measures have been proved at depth in many boreholes and form outcrops at two main localities. The dolerite cropping in the Wednesfield area [950 005] and at Heath Town [935 989] forms part of a massive steep-sided intrusion or stock from which sills emanate at depth beneath the whole of the outcrop of the Coal Measures. One of the thickest sills rests close below the Fireclay Coal at New Cross Farm [940 995], from where it transgresses to successively lower levels southwards. It lies just above the Bottom Coal at Bowmans Harbour [993 994], where it is 36.6 m thick, is found between the Bottom and Mealy Grey coals at Priestfield No. 78 Pit [9441 9745] (15.5 m thick), and is at the level of the Mealy Grey at Deepfield No. 4 Pit [9413 9504] (6.1 m thick).

Etruria Formation

The Productive Coal Measures pass up conformably into the Etruria Formation, a redbed sequence of mudstones and siltstones, commonly variegated in colours of grey brown and yellow, and with a blocky unbedded texture resembling that of a seatearth. Lenticular sandstones known as `espleys' within the sequence are typically coarse-grained and occasionally conglomeratic, with angular clasts including Cambrian quartzite, Silurian sandstone and rotted igneous rocks. The top of the formation is marked by an erosional unconformity at the base of the Halesowen Formation. West of the Boundary Fault, the formation is estimated to be between 60-200 m thick, but in areas such as Penn it is locally absent. Outcrops are confined to slivers preserved within the Western Boundary Fault complex between Goldthorn Park and Monmore Green.

Halesowen Formation

To the west of the Western Boundary Fault, the presence at depth of the Halesowen Formation is inferred from the sequence proved in British Coal boreholes at Penn. The Halesowen Formation marks a return to Coal Measure type sedimentation, consisting of grey-green mudstones and siltstones, and thick beds of yellow-weathering, locally pebbly sandstone. Thin coals are present but are too thin and sulphurous to have been worked. The formation ranges in thickness between 100-110 m.

Keele Formation

The Keele Formation is the lowest division of a thick Permo-Carboniferous redbed sequence that contains few lithological markers, and is known mainly from sketchy well records dating from the turn of the century. The formation was only fully proved in the Penn boreholes where it ranges in thickness from 208-268 m. It is predominantly argillaceous, consisting of red-brown and purple calcareous mudstone in the lower part of the succession but with beds of red-brown, purple and lilac fine-grained sandstone becoming increasingly common in the upper part. Mudstone-flake breccias and caliche nodule horizons are widely developed.

The subcrop generally lies below the level of the majority of water boreholes in the Borough, but the Midlands Counties Dairy bore [9090 9778] penetrated the formation to an estimated depth of 69 m (Figure 8).

Enville Formation

The Enville Formation is lithologically similar to the underlying Keele Formation, but is distinguished by a higher proportion of sandstones, pebbly sandstones, and pebble conglomerates rich in dolomite and chert clasts. The sandstones are evenly distributed throughout the sequence, but are impersistent laterally, wedging out and splitting. The formation ranges in thickness from 90-110 m but is poorly exposed, and over a large area of Springfield it is included for mapping purposes with the overlying Clent Formation (see below).

Permian

Rocks of presumed Permian age comprise the Clent (Breccia) Formation, which crops out through central Wolverhampton, and the Bridgnorth Sandstone, which is not present at crop but was proved in boreholes in the west of the Borough.

The **Clent Formation** consists of sandstones with thin beds of red mudstone. Pebble breccias, which are commonplace in the type area in the Clent Hills are only present as thin lenses. There is considerable difficulty in distinguishing this lithofacies from beds of the underlying Enville Formation, consequently, in the central and north-eastern parts of the Borough, where the Clent Formation is assumed to be present, it is included for mapping purposes with the Enville Formation. Estimated thicknesses are in the order of 90-110 m.

The **Bridgnorth Sandstone** has been proved beneath the Kidderminster Formation in water boreholes at Tettenhall Pumping Station and at Dunstall Hall Works. Evidence from farther south suggests that the formation is only present west of the line of the Stapenhill Fault. In boreholes the formation consists of red-orange, fine- to medium-grained, feldspathic sandstone, up to 54 m thick. The occasional presence of `millet-seed' grains are indicative of an aeolian origin.

Triassic

Triassic rocks, comprising the Sherwood Sandstone Group, crop out over most of the eastern half of the Borough. Three formations are present, comprising in upwards sequence, the Kidderminster Formation, Wildmoor Sandstone and Bromsgrove Sandstone (Figure 8).

The **Kidderminster Formation** (formerly called Bunter Pebble Beds) comprises 80 to 130 m of red-brown medium to coarse grained sandstone interbedded with pebble- to cobble-size conglomerate and subordinate mudstone. The conglomerate-dominated facies, gives rise to prominent topographic features that extend from Bushbury Hill in the north of the district to Goldthorn Hill in the south. The formation rests unconformably on the eroded surface of the Clent Formation and is overlain by the predominantly non-pebbly Wildmoor Sandstone.

The **Wildmoor Sandstone** crops out beneath the western suburbs in a broad tract extending from Dunstall Park through Bradmore to Penn. The outcrop is characterised by undulating topography, low dips to (to the NNW) and a distinctive red-brown sandy soil. The formation, estimated at between 150 and 190 m thick, consists of red-brown and orange, fine- to medium-grained feldspathic sandstone; generally the formation is characterised by an absence of pebbles (Plate 2a). Towards the top of the formation a red mudstone unit is common. The fine grain-size and soft, poorly cemented nature of the sandstone means that in the weathering zone it generally breaks down to a fine sand, a characteristic that made it ideal for working as moulding sand. Disused quarries adjacent to Smestow Brook testify to its former exploitation.

The **Bromsgrove Sandstone**, of which some 105 m are exposed, is the upper division of the Sherwood Sandstone Group. The formation rests disconformably on the Wildmoor Sandstone, above which it frequently forms a marked escarpment such as at Tettenhall Wood and around Dunstall Hill. Red-brown sandstones, pebbly sandstones and conglomerates with a strong calcareous cement are typical (Plate 2b, c). Upward-fining cycles capped with thin mudstones can be recognised in continuous sections.

3.4 Structure

[Figure 9]

The structural map of the area (Figure 9) shows the principal faults and folds, and indicates the general disposition of the main rock units on either side of the Western Boundary Fault. Structure contours have been drawn on the base of the New Mine Coal for the exposed coalfield, and on the base of the Kidderminster Formation within the area of the Triassic crop.

Faults

The most important faults in the Borough are the Western Boundary and Bushbury faults, which have throws down to the west of around 900m and 350m, respectively. Soil gas measurements of radon levels have been used successfully in the Nordley Hill area [944 009] to pin-point the position of the Western Boundary Fault beneath thin glacial cover.

Within the exposed coalfield the majority of faults have throws of less than 50 m; exceptions are the South Bentley Fault (90 m) and the Lanesfield Fault (64 m). More than half the faults trend either east-north-eastwards or south-south-eastwards, forming a conjugate set of tensional faults relating to the local folding. A further set runs east-west, and includes the North and South Bentley Trough faults, which form a graben separating the thicker Coal Measure sequences of the Ashmore Park area from those farther south.

Folding

The tightest folds in the area affect Silurian strata as exemplified by the north-north-west-trending pericline of Hurst Hill [928 940], where flanking dips up to 75° are recorded. The Productive Coal Measures, in contrast, are generally only gently folded. The principal structure is a gentle synclinal fold whose axis runs south-south-east from Monmore Green [930 980] through Stow Heath [935 972] to pass between Ladymoor [941 952] and Highfields [948 953]. The structure plunges gently southwards, bringing in successively higher measures in that direction. Dips are generally below 10°, but reach 26° on the western limb at Spring Valley [9324 9525] where the structure steepens into a north-south orientated, eastward-facing monocline. In the Ashmore Park area, the strata dip generally north-west, although dips vary locally between west-south-west and north-north-east.

The structure west of the Western Boundary Fault is obscure due to lack of exposure, but examination of surrounding areas suggests the presence of a gentle anticline, with its axis running north-south through Wolverhampton. The Triassic strata are only affected by a gentle dip to the west-north-west. They form the south-eastern rim of the Stafford Basin whose centre lies well to the north-west.

3.5 Mining [Figure 10]

Deep mined coal

Coal and associated ironstone and fireclay seams have been mined in the exposed coalfield since mediaeval times. Most of the named seams have been worked, apart from the Upper Sulphur Coal, which is thin and of poor quality. South of the Bentley Faults the most extensive workings are in the Thick Coal, New Mine Coal and Fireclay Coal seams. The `pillar and stall' method of extraction was favoured for the thicker seams, and the longwall method for the thinner coals and ironstones. Workings are comparatively shallow, extending from close below surface in the Bowman's Harbour area, to a maximum depth of around 40 m below OD in the south of the Borough.

North of the Bentley Faults most of the seams down to the level of the Deep Coal have apparently been worked.

In the concealed coalfield, deep mined coal has been extracted from beneath Bushbury in headings driven from Hilton Colliery. The two seams to have been worked are the Eight Feet and Park coals, which lie at depths of between 420 and 470 m below OD. The only other workings are in the Thick Coal which has been mined at depths of between 425 and 450m below OD in extensions from Baggeridge Colliery.

Limestone

The Upper and Lower Quarried Limestone members have been mined locally adjacent to their outcrops on Cinder Hill.

Opencast workings

Modern opencast working has only taken place at a few sites.The New Cross Farm site [940 995] was worked in 1944, and now adjoins a modern major redevelopment at Bowmans Harbour; there have also been at least two private excavations at Ettingshall Park [923 955; 929 955]. It is likely, however, that many of the seams of coal and ironstone, and particularly the Thick Coal, were worked by opencast methods near their outcrops early in the mining history of the area.

Map 10 shows the extent of undermining for coal, ironstone, fireclay and limestone based on 1:25 000 scale computer plots provided by British Coal (now the Coal Authority). Coverage is complete except for sheet SJ90SE for which only partial data have been secured.

The sites of known shafts form a separate dataset. The positions are generalised from records held by the Coal Authority, and should only be used as a guide to the density of shafts in the area.

3.6 Superficial (drift) geology

[Figures 11 - 15]

Figure 11 is a rockhead contour map; figures 12 to 15 provide information on the distribution, thickness and composition of the superficial deposits.

Wolverhampton lies just within the limit of the Devensian glaciation. At its maximum expansion the ice sheet probably covered the whole of the district, except possibly for the highest ground in the south of the Borough. The depositional products of the glaciation are dominated by till which covers all but the most prominent bedrock features. The till is accompanied locally by sequences of outwash sediments (sand and gravel) and glaciolacustrine clays. Contours drawn on the bedrock surface (Figure 11) show that the drift infills a pre-existing topography dominated by the Smestow valley system in the west, and by the Moxley Channel in the east.

In order to obtain more information on the nature of the glacigenic sediments, nine shell-and-auger boreholes were drilled at disparate sites across the Borough. Continuous U100 core samples were taken through the till, and representative bag samples collected of unconsolidated deposits. All but one borehole penetrated to bedrock. Tests were conducted in the laboratory to determine the particle size, composition and permeability of the till; in addition, pebble counts and grading analyses were carried out on sand and gravel samples. The results are reviewed below.

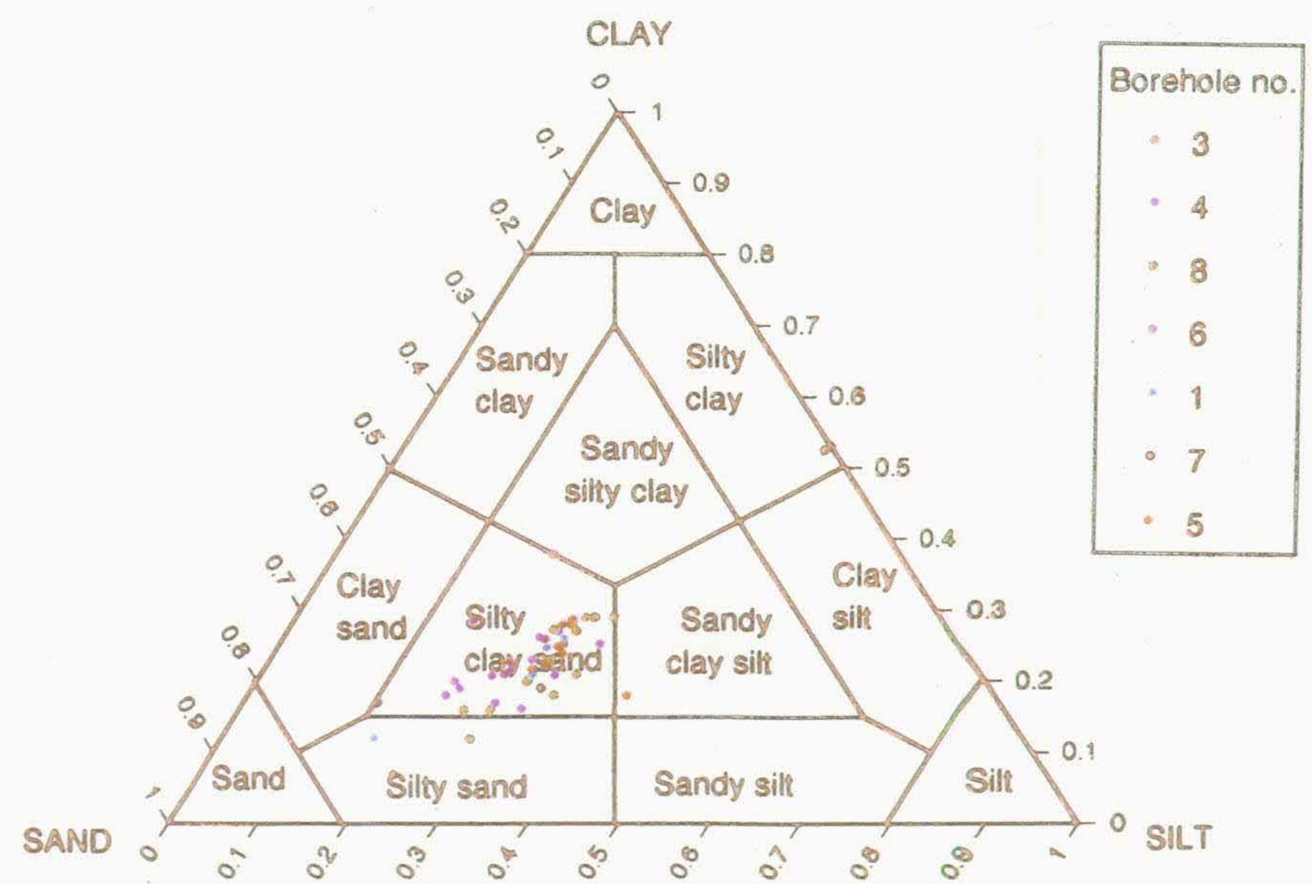
Till

Till occurs as broad spreads covering most of the lower ground formed by the less resistant Carboniferous and Triassic formations (Figure12). Only the Kidderminster Formation and the Bromsgrove Sandstone are substantially drift-free. The till sheet is generally thin (less than 4m) in the north of the Borough but thickens to around 12m in central districts (West Park, Springfield) and over larger tracts in the south-east (between East Park and Bilston). Thicknesses of around 35m are recorded in parts of the Moxley Channel, where the till is intercalated with other glacial deposits.

Lithologically, the till consists of a reddish brown, stiff `clay' with well rounded to sub-angular pebbles, cobbles and boulders (erratics), representing material incorporated into the ice-sheet during its south-eastward advance into the region (Plate 3). Erratics (> +2mm) constitute, on average, about 10 per cent of the bulk of the till, and consist of a mix of locally derived material (Triassic and Carboniferous sandstones and siltstones) and clasts derived from farther afield (mainly Welsh greywackes and igneous rocks). Exotic clasts include granitoids and occasional marine shell fragments. A sandy facies of the till has been mapped in the south-east of the Borough between Bradmore and Penn.

The evidence of the borehole sampling programme suggests that the matrix of the till is remarkably homogeneous both in respect of its particle size and clay mineralogy (Kemp and Mitchell, 1994). The triangular plot of particle size data, based on 49 samples from seven boreholes, identifies the majority of the samples as `silty clay sands' (Figure 14). These have a uniform clay mineral assemblage of illite, corrensite, kaolinite and chlorite.

Figure 14. Triangular plot of normalised particle size data (<2mm) for till samples from the Wolverhampton area.



Falling-head permeability tests were carried out on seven till samples at the laboratories of the Engineering Geology and Geophysics Group. The results, discussed in detail by Hobbs (1994), show the tills to be `practically impervious' or of `very low' permeability, and typical of `intact clays' (Head, 1994). The range of mean permeability values is from 2.6×10^{-10} to 1.7×10^{-9} m/s.

Glaciofluvial Deposits (Sand and gravel)

Red-brown, fine- to medium grained sands, pebbly sands and gravels deposited by glacial meltwaters are frequently found in association with the till. The deposits can be divided into two somewhat arbitrary categories depending on the processes involved in their formation.

Channel deposits

The valley of **Smestow Brook** marks the course of a meltwater channel complex which can be traced in boreholes and at outcrop from Stafford Road Gasworks, through Dunstall Park and then south-westwards along the foot of the Tettenhall escarpment. Along parts of the valley, the modern alluvium conceals deposits of silt, sand, and gravel, locally upwards of 19 m thick (e.g. borehole at [8942 0023]). Exposures of sand and gravel, sandy till and `pebbly drift' infilling channels above the present river level are reported from the foot of the Tettenhall escarpment at Compton and Wightwick (Morgan, 1972; Whitehead and others, 1928). Whitehead suggested that these were relics of old, probably sub-glacial channels produced by marginal or sub-glacial streams.

Linked to the Smestow Brook system is a separate channel that extends northwards from Dunstall Park towards Pendeford. A borehole transect across the channel just to the south of Oxley Moor Bridge proved sand and gravel to depths of 17 m resting directly on bedrock . It is possible that this second channel was eroded during a period when the main Smestow channel was blocked by ice.

The **Moxley Channel** is a buried bedrock channel that extends from March End south-southeastwards beneath The Lunt to beyond the Borough boundary. The channel has no surface expression but is infilled to a depth of 36 m with a variety of drift deposits including sand and gravel, till and glaciolacustrine clays. The channel may have originated as a pre-glacial valley but if the rockhead contours (Figure 11) accurately reflect the channel form, then it appears to be unevenly graded and must, therefore, have been deepened by sub-glacial erosion.

The sands at **Ettingshall** [930 962] and **Parkfield** [922 960] are also regarded as infilling channels, though the contour evidence is more equivocal.

Basal (sub-till) deposits

Boreholes in many parts of the Borough reveal extensive sheets of sand and gravel, rarely more than 1-2 m thick, interposed between the base of the till sheet and bedrock. The gravels contain erratics that indicate a clear association with the overlying till. Such deposits may represent fluvioglacial outwash deposited in front of the advancing ice sheet; alternatively they may have been deposited by streams flowing beneath the ice.

Intra-till and supraglacial deposits

Pods and lenses of sand and gravel enclosed within, or forming a surface capping to till, form a small but hydrogeologically important part of the glacial sequence. These deposits are reported from many parts of the Borough, but are not generally mappable. A BGS borehole at Bantock House [8959 9798], located on an outcrop of sandy till, proved an interleaved sequence of sands and silty clays (5 m), before entering a more consolidated till unit below. If the above sequence is typical of the sandy till facies, then there is the potential in these areas for the development of a perched water table.

In an attempt to define areas in the Borough where glaciofluvial deposits contribute significantly to the drift sequence, the total thickness of sand and gravel was calculated and plotted for each borehole in the database. The results (Figure 15) clearly define the Smestow and Moxley Channels but otherwise show no consistent pattern. Interestingly, the area mapped as sandy till does not figure as being any more sandy than till in other parts of the Borough.

Glaciolacustrine Deposits (silt and clay)

These deposits were laid down in lakes associated with the ice-sheet, where water was temporarily ponded. Most provings are in the Moxley Channel, where red-brown glaciolacustrine clays are present beneath till. A borehole on the edge of the channel at St Chads [9561 9726] proved 8 m of structureless clay without bottoming the deposit. Samples from this borehole show a mineralogy similar to that of the overlying till sheet (Kemp, 1994).

Alluvium

The streams in the Borough are flanked by narrow, alluvial floodplain deposits. These consist of silt and clay overlying coarser beds of sand and gravel. The alluvium of Smestow Brook forms a tract about 100 m wide, and is about 5 m thick.

3.7 Made Ground

[Figures 16]

The original land surface in Wolverhampton, in common with most heavily urbanised industrial areas in the Midlands, has been extensively modified by man.

Made ground deposits are spread widely across the Borough, especially in the area of the exposed coalfield. Figure 16 shows the distribution of the fill, and gives an estimate of its thickness based on borehole provings. Colliery spoil is the predominant fill material, with a thickness that normally varies between 4 and 10 m, exceptionally reaching 20 m. At the turn of the century much of this material was dumped haphazardly in waste mounds at the pitheads, leading to local waterlogging. As urbanisation proceded the material was levelled, so that nowadays it seldom forms topographical features and its extent is only known from borehole and trial pit data.

In the long-established industrial areas, colliery spoil is frequently mixed with other fill types, often belonging to different generations. Such deposits include foundry sand, building rubble, and variable quantities of metal, timber, glass, plastic and other miscellaneous by-products of the paint, metal finishing and electrical industries. Some of this fill has been buried in former quarries and pits and is more properly classified as Made and Worked Ground (see below). The borehole database is too sketchy to attempt any categorisation of these deposits; however, their distribution is likely to be linked to manufacturing centres that have grown up since the turn of the century (see section 4).

3.8 Made and Worked Ground (Landfill)

[Figure 17]

A survey of former landfill sites carried out by Wolverhampton's Environmental Health and Consumer Service Department was completed in 1991, and provides the most up-to-date information on this topic. The survey identified 44 completed sites, whose locations are shown on Map 17. For each site, the type of waste, where known, has been recorded, together with information on the volume, depth and age of the waste (Table 2). Eighteen of the sites contain domestic waste, the remainder contain a variety of deposits including foundry sand, slag, building rubble, canal dredgings and sewage sludge. Each of the sites identified was considered by the Borough to be a potential source of landfill gas, and a programme of gas monitoring was undertaken to assess this risk. Eight sites were identified as having high levels of gas production, and six had locally high levels; in the remainder gas levels were negligable. In the high risk sites remedial action has involved the installation of gas extraction equipment.

4. LAND USE

[Figures 18, 19]

Insight into the way urbanisation has proceded within the Borough since the turn of the century is provided by two land-use maps compiled for the 1900s and 1990s. These show successive stages in the development of residential, amenity and industrial centres with time, and provide a basis for interpreting the geochemical data (Section 5.) The older maps have been compiled from early editions of Ordnance Survey 6-inch scale topographic maps; the modern land-use map is based on the Unitary Development Plan prepared by Wolverhampton MBC. The categories that have been adopted on each map are defined below.

- Roads
- Water Courses (canals, rivers, ponds)
- Open spaces
  - Public open spaces and parks
  - Sports grounds and playing fields
  - Cemeteries
  - Allotments
  - Green Belt
  - Other Open Spaces. This includes Development sites and Ground disturbed by mining activity (1900s map)
- Railways (including disused lines and marshalling yards),
- Residential areas.
- Major industrial areas.
- Completed landfill sites (1990s map only).

Table 2. Landfill sites within Wolverhampton.

Number	Site	Grid reference	Volume (m^3)	Depth (m)	Age of waste (yrs)	Type of waste
2	Phoenix Park	391800 296700	617700	14.5	27	Domestic waste
4	Brickheath Road	393200 299000	257400	16.5	16	Domestic waste
7	Sandy Lane, Aldersley	389600 300800	56250	12.5	40	Domestic waste
10	Weddell Wynd	395600 294400	200000	20	25	Domestic waste
11	Gorsebrook Road	391000 300400	27000	6	12	Domestic waste
13	Bushbury Hill	392600 302300	128000	16	31	Domestic waste
15	Sandy Hollow	388200 298800	160000	8	35	Domestic waste
16	Thompson Avenue	392200 297100	183600	12	27	Highways & domestic waste
18	Ettingshall Park	392300 295600	483000	10	25	Domestic waste
19	Taylor Road	392700 296300	90000	4.5	28	Domestic waste
22	Wednesfield Sewage Works	395300 299500	220000	5	15	Sewage waste
24	Hinchliffe Avenue	393800 294500	36000	6	20	Unknown, possibly domestic waste
26	Hall Green Street	395130 294800	164000	4	30	Soil, unknown origin
28	The Keyway	395900 297900	195000	5	4	Inert foundry waste
31	Broadmoor Road	394600 295500	24000	12	30	Unknown
37	Monmore Green Stadium	393300 297500	Unknown	Unknown	50	Unknown
40	Windsor Avenue Playing Fields	389400 296500	19500	3	30	Highways waste
43	Neachells Lane II	394900 298500	Unknown	Unknown	30	Unknown
30	Ex Bilston Steelworks	393700 295400	4420000	17	8	Inert foundry sand and building rubble
33	Aspen Way	390000 298400	Unknown	Unknown	50	Unknown
35	Dock Meadow Drive	393400 295600	110000	10	30	Unknown
39	Bradmore Recreation Ground	389400 297000	9000	3	30	Highways waste
1	Stowheath Lane	394200 297900	634400	8	22	Domestic waste
36	St. Leonards School	393900 296700	Unknown	Unknown	50	Unknown
29	Bowen Street, Parkfield	392400 296300	8000	4	35	Inert waste
34	Chanterelle Gardens	390500 295700	60000	10	36	Inert building waste
41	Northwood Park	392400 302900	10800	3	40	Unknown
32	Withy Road	394200 295600	7800	3	40	Unknown
44	Merrills Hall Lane	394900 299600	12000	3	25	Inert waste
9	Alexander Metals, Darlaston Lane	396600 297200	910000	10	15	Foundry sand, slags and building rubble
3	Kitchen Lane	396600 302670	512550	8.5	24	Domestic waste
6	Neachells Lane	394600 298800	285200	4	6	Domestic waste
8	Ashmore Park	396100 302200	248000	8	25	Domestic waste
14	Pendeford Tip	389200 302800	334200	6	10	Hardcore, subsoil, highway and cleansing waste
17	Carder Crescent	394800 295700	165000	15	40	Domestic waste
20	G R Smithson, Stafford Road	391300 304100	12000	4	1	Inert waste
23	Lunt Sewage Works	396500 296400	755000	5	15	Sewage waste
25	Ladymoor Road	394300 295000	15000	5	27	Canal dredgings
27	Wolverhampton Road	394100 299900	284000	8	18	Inert foundry waste
38	Parkfield School	392200 296200	14000	4	25	Unknown
42	Deansfield School	394200 298800	12000	4	25	Unknown
5	Bowmans Harbour	393700 299500	7089000	30	29	Domestic waste
12	Bridgnorth Road	387500 298400	290400	8	40	Domestic waste
21	Regis Road (STWA)	388400 300100	96000	6	2	Inert foundry sand

5. GEOCHEMISTRY

5.1 Introduction

Regional geochemical maps of the UK have been prepared by the British Geological Survey since the early 1970s to supplement geological mapping and are now available for much of Northern Britain. However until recently, the regional survey has not covered built areas. The present pilot study of the Metropolitan Borough of Wolverhampton has provided an opportunity to apply well proven geochemical techniques to an urban environment.

Rural soils are well documented and soil maps exist for many areas but there is much less information dealing with soils in the urban environment. The Soil Geochemical Atlas of England and Wales (McGrath and Loveland, 1992) presents data based on samples taken at 1 per 25km^2 but no attempt was made to sample urban soils. The urban soils of Britain alone cover 1.7 million hectares (Bullock and Gregory, 1995) of which 12% is classified as open space.

The main problems within urban areas are that soils have been damaged physically, chemically and biologically. Many areas are contaminated, soils are compacted, suffer from poor drainage or have a high stone content. A particular cause of concern within urban areas is contaminated land.

The geochemical maps produced for the Borough show the distribution of a range of elements in soil generally referred to as Potentially Harmful Elements (PHEs) and results are presented as a series of single element maps. However, it must be emphasised that this provides only a guide to dispersion and further more detailed sampling would be required to investigate specific sites. Additionally surface water samples and bottom sediment samples have been collected from streams and canals and analysed for a range of inorganic and organic elements.

The geochemical data have been examined with the aid of the GIS system, using other spatial datasets to aid interpretation including land use, geology, drift deposits and made ground. Available information relating to contamination and landfill sites within the borough has been collated from local authority records, in order to assist the interpretation.

Other potential geohazards investigated include methane, carbon dioxide and radon.

5.1.1 Background

During the 19th century the UK underwent rapid industrialisation and urbanisation, with little or no legislation controlling potential hazards from either natural or man-made sources. In British cities heavy industry and housing grew up side by side, and, as development continued into the 20th century, the effects on the environment of heavy industry and the use of natural resources, particularly the burning of coal, became apparent. Implementation of The Clean Air Act of 1956 was in direct response to the dense smogs that engulfed many British cities at that time. Today, although most heavy industry has disappeared from city centres it has left a legacy of contamination.

Increased urbanisation and planning directives, such as the green belt policy, have increased pressure to re-develop land within city boundaries. Therefore new housing, industrial and recreational amenities are being developed on recycled brownfield sites where it is essential to have comprehensive information on former use.

5.1.2 Contaminated Land

The first Government action relating to contaminated land was the establishment of a Interdepartmental Committee on the Redevelopment of Contaminated Land (ICRCL). The committee provided general guidance on site redevelopment and introduced the 'trigger' advisory levels for contaminants in soils.

Parliamentary interest resulted in the House of Commons Environmental Committee investigation into contaminated land which began in 1989. It was recognised there was a need for better information on the type and extent of contaminated land and in 1990, in response to the Parliamentary Environment Committee, the Government made provision in the Environment Bill for local authorities to compile registers of contaminated land. However, registers were not initiated following concern they may cause land blight.

The introduction and subsequent withdrawal of local authority registers (Section 143 of the Environmental Protection Act 1990) has meant there is now a paucity of information on contaminated sites. The lack of collated information prompted the Parliamentary Office of Science and Technology (POST) to investigate the issues involved and a report on contaminated land was published in October, 1993.

Recently a new statutory framework has been presented (DoE 1994) for dealing with contaminated land involving local authorities and the new Environment Agency (successor to the National Rivers Authority (NRA), Her Majesty's Inspectorate of Pollution (HMIP) and the Waste Regulation Authorities (WRAs)) which forms part of the Environment Act, 1995. The Government is committed to a "suitable for use" principle and "polluter pays" policy for the control and treatment of contamination.

5.2 Potentially Harmful Elements (PHEs)

There are a wide variety of *potentially* harmful substances that may be present in the urban environment but the common ones are as follows:-

1. Inorganic substances including heavy metals and toxic elements, cyanides, oxidants, corrosive substances such as acids and alkalis and materials such as asbestos which are harmful because of their physical nature.
2. Organic compounds including coal tar, phenols, petroleum products, solvents and chlorinated compounds such as polychlorinated biphenyls.
3. Gases including methane, carbon dioxide, carbon monoxide and radon.

Investigations in Wolverhampton have concentrated on a selected number of these substances in particular, the Potentially Harmful Elements (PHEs), Polycyclic Aromatic Hydrocarbons (PAHs), methane (CH_4), carbon dioxide (CO_2) and radon gas (Rn).

PHEs include the "toxic elements" and the "heavy metals". The "toxic elements" have no known biological function and include arsenic, cadmium, mercury, lead, thallium and uranium. The term "heavy metals" is not precisely defined but generally includes metals and metalloids associated with pollution and toxicity.

5.2.1 Health effect of PHEs

All living things require certain levels of minerals or elements to survive. Many elements are essential to plants, animals and human health at low concentration but may be toxic at higher concentrations.

The history of the discovery of PHEs and their effects in the food chain are documented by Davies (1980), Thornton (1983), Thornton and Howarth (1986), Alloway (1990) and Fergusson (1990).

In the past two decades there has been a number of studies in the UK into the health effects of increased levels of PHEs in the environment. Studies in the urban environment have tended to concentrate on Pb and to a lesser extent Cd because of concerns over increased levels due to traffic pollution. Studies have also concentrated on the heath effects on children who are seen to be morel vulnerable to increased levels of PHEs because of greater exposure to soil through play in gardens, open ground, play areas and derelict land. Studies by Barltrop (1979) have shown that although increased levels of lead in childrens' hair, blood and urine samples are found in areas of high environmental lead, the actual effects on health are inconclusive. An extensive study was conducted by the DoE into the health effects of high environmental Cd after the Wolfson Geochemical Survey (Webb and others, 1973) identified areas of high Cd in stream sediments around the village of Shipham in Somerset (Morgan and Simms, 1988). Increased levels of Cd were found in garden soils, home grown vegetables, house dust and in human blood samples. No adverse health affects were noted although long term monitoring of the population continues.

The majority of investigations into urban contamination have involved the collection of soil, sediment, dust and water samples (Thornton and others, 1985). The majority of studies collect soil samples on a grid basis from gardens, open areas, parks, derelict land etc. In addition to assessing the 'total' concentration of PHEs, in these media, assessment of the take up of PHEs in the food chain has been carried out by several workers using selective analytical methods to determine element and compound speciation and availability to plants and animals. The mapping of surface soils and dusts shows the amount and dispersion of airborne contaminants. It is possible by these methods and the application of meteorological data to map contamination from chimneys, traffic fumes, etc. Deeper soils show element levels less affected by airborne contamination but reflect past industrial contamination.

Levels of PHEs can vary considerably between different geological soil types by up to a factor of 100 for some elements. In general, lower concentrations occur in chalk and sandy soils and higher values occur in soils derived from igneous rocks. It is therefore important when considering contamination to establish local background levels typical of the known geology and soil type. In the UK, background levels for stream, sediments and soils can be ascertained from the BGS Regional Geochemical Atlases, the Wolfson Geochemical Atlas and the Soil Survey Geochemical Atlas of England and Wales.

5.3 Sources of contamination in the urban environment

Contamination in the urban environment can in some cases be from natural sources particularly in the case of gases. However, the majority of contamination, is likely to be associated with human activity. There are a wide range of past and present industrial and domestic activities that could potentially cause contamination within the Borough, some of which are listed below:

- Coal mining activities
- Smelters, foundries, steel works, metal processing and finishing
- Heavy engineering
- Electrical and electronic equipment manufacture and repair
- Gasworks, coal carbonising plants and power stations
- Petroleum storage and distribution sites.
- Manufacture of inorganic and organic chemicals
- Rubber industry and tyre manufacture
- Paper and pulp manufacturers and printing works
- Timber treatment
- Food processing industry
- Railway depots, sidings, works and road haulage depots
- Landfill and incineration of waste
- Sewage works
- Scrap yards
- Dry cleaning premises

5.3.1 Buildings

The majority of building materials are relatively inert, though demolition of older buildings and industrial premises may lead to contamination of soils with heavy metals including lead from paint.

5.3.2 Households

Heavy metal accumulation in household gardens is well documented (Davies, 1978; Thornton and Jones, 1984; Thornton 1995), Lead concentrations in surface soils (0-15 cm deep) tend to increase with the age of the house. Sources of metals in garden soils include the disposal of fossil fuel residues (ash and soot), household refuse, bonfires, fragments of lead-containing paints, the long-term application of phosphatic fertilisers (Cd) and deposition of atmosphere particulates from vehicle emissions, the burning of fossil fuels and industrial processes.

5.3.3 Waste

Toxic metals are present in varying levels in domestic and industrial wastes which are often mixed resulting in isolated pockets of hazardous substances including phenols, organo-tin compounds, cyanides and asbestos. In the United Kingdom some 90% of refuse is now disposed of in landfill sites from which there is usually little loss of metals into neighbouring soils and watercourses, though leachates may contain other more soluble constituents, be extremely acidic and contaminate groundwater.

5.3.4 Water pollution

Waste waters from a whole range of activities associated with urban development, such as food processing, laundries and breweries often contain high concentrations of metals. Arsenic is present in household detergents and waste water from many urban activities contain high levels of heavy metals. Storm run-off water from towns contain high levels of lead and significant quantities of zinc and copper (Chow, 1978). Sewage sludge can also contain high levels of many metals (Berrow and Burridge, 1981; Charney, 1985).

5.3.5 Transport

The majority of lead in the air in the United Kingdom comes from the exhaust gases of petrol engines (Royal Commission on Environmental Pollution, 1983). It is now widely accepted that the settling out of lead-rich aerosols derived from the exhaust fumes of cars results in the contamination of surface soils. Lead in soil is virtually immobile and therefore the existing contamination is, in essence, a permanent phenomenon.

Large areas of railway land including tracks, sidings, workshops and marshalling yards may have scrap metal, oil and debris from rolling stock in the soil, even following reclamation. Canals may have similar debris as well as accumulations of dredged materials comprising organic-rich sludge and sometimes heavy metals resulting from spillage of cargo, motor fuel and paint.

5.3.6 Smelting

Metal smelters, both primary and secondary, result in contamination of the land surface and drainage through stack and fugitive emissions, dissolved species in liquid effluent, the dumping or erosion of particulate slag, transport and spillage of metal concentrates. Atmospheric emissions may be very large but depend on the technology employed in the plant, ore composition and the air pollution control system. Soil contamination around smelters from airborne dispersion has been studied at several locations. Generally, contaminated ground describes an ellipsoid with the long axis oriented along the direction of the prevailing wind. Contamination is most severe within 3km of the smelter, decreasing exponentially until background levels are reached at 10-15 km (Davies, 1980, 1983). Elevated levels of Ni, Cu, Zn, Cd, As, Sb, Ag, Se, Hg and Pb are often recorded in these areas (Little and Martin, 1972), other metals and metalloids, such as F, Mo, Tl, Sn, W, Au and Bi may also be enriched depending on the type of smelter, but have not been determined by many studies. Fluorine is a particular hazard associated with aluminium smelters. The effect of legislation has reduced the emission of toxic metals from smelters, but the older and larger the smelting operation the greater the probable contamination.

5.3.7 Extraction and combustion of fossil fuels

Coal mining has now ceased in Wolverhampton but it has left a legacy of waste materials and a large area, particularly in the south-east, underlain by ash and slag. Drainage from the old coal mines, leachates and run-off from coal and waste piles may be extremely acid due to the oxidation of sulphides and may contain high levels of Fe, Mn, Cu, Ni, Zn and appreciable amounts of other heavy metals such as As and Pb (Barnhisel and Massey, 1969 and Kagey and Wixon, 1983) which can contaminate soils.

Sites of disused and demolished power stations will give rise to contamination from coal, pulverised fuel ash, which is alkaline (pH 11-12) and contains soluble salts, in particular, boron. Atmospheric deposition of trace metals from all sources suggests that Cu, Zn, Ag, Cd, Sb, Se and Pb can be expected to exhibit the greatest increases due to human activity.

Metals enriched in soils around coal-burning plants include Ti, Fe, Co, Cr, Ni, Cu, Zn, Cd and Hg. Some ash is dispersed in the atmosphere, the remainder is collected, sometimes as a slurry in settling ponds, and either dumped at infill sites or spread on land. Element concentrations in ash vary with particle size, with chalcophile and volatile elements concentrated in the finer fractions. Elements concentrated in fly-ash include B, Be, V, Ni, Mn, Cu, Zn, Cd, Mo, As, Se, Sb, Te and in slurry form may be acid or strongly alkaline (range pH 3.3-12). Leachates under certain conditions contain B, V, Co, Cr, Mn, Ni, Cu, Cd, As, Se and Zn (Kagey and Wixon, 1983). A comparison of metal concentrations in uncontaminated soil and fly-ash indicates that the disposal of fly-ash on land, which can be used to provide plant nutrients and reduce acidity, may give rise to B, V, Co, Ni, Cu, Zn, Mo, Cd, As, Se and Pb anomalies.

5.3.8 Manufacturing industries

These are many and varied and the pollutants that can be produced are equally varied. Generally the older the industry the more likely it is to have produced substantial contamination of nearby soil and drainage. Many industries are liable to give rise to polymetallic anomalies in soil but a few, such as leather tanning, are associated with only one or two metals.

Chemical works, gas works and oil refineries give rise to a wide range of contaminants, some of which may be dispersed in the air whilst others contaminate the site or adjacent soils and streams. Potential pollutants from chemical works include a wide range of acid and alkaline substances, heavy metals and metalloids such as Cr, Cu, Zn, Cd, Sn, Hg and Pb. Agricultural chemicals and fertiliser plants may be associated with a very wide range of pollutants whilst waste waters from explosive plants may contain Cu, As, Hg and Pb. Oil refineries and oil products are potential sources of Cr, Ni, V, Co, Cu, Zn, Cd, Mo, As and Pb concentrations (Ramondetta and Harris, 1978) whilst petroleum cracking catalysts and their products have been traced as the source of light rare-earth anomalies. Old gas works may be contaminated with coal and coal residues, spent iron oxides, cyanides, sulphates and a range of organic compounds and associated tars.

Almost all metals may be present in anomalous amounts associated with steelworks, foundries, electroplating and finishing works. The cleaning and etching of bare metal surfaces in a wide range of metal finishing and plating processes is a particularly major source of contaminants in drainage systems; high levels of Cr, Ni, Cu, Zn and Cd may be produced (Forstner and Wittman, 1981). Predictably, battery manufacture may generate waste rich in Ni, Cd, Zn, Sb, Hg and Pb.

The storage, processing, recycling and disposal of scrap materials results in site contamination and soils will often contain a range of toxic substances including Heavy metals, waste oil, PCB's and other organic and inorganic substances.

Paint and dyestuff industries use a wide range of pigments and raw materials and discharge elevated levels of Cr, Cu, Cd, Se, Hg and Pb in the waste water.

Electrical and electronic industries may produce waste containing Cd, Zn, Se, Cu and Pb (Asami, 1984). Zn, Sn, Pb and Cd are employed in the manufacture of synthetic rubber and/or plastics as stabilisers and pigments. The leather and textile industries use chromates and dichromates, resulting in effluent which is a major source of Cr enrichment in sediments (Forstner and Muller, 1973). The glass industry also uses Cr as well as Pb.

5.4 Soil sampling in Wolverhampton

5.4.1 Method of collection.

Sample points for the collection of soils were predetermined on a regular square grid to give a density of 4 samples per $1km^2$. Each kilometre square on the Ordnance Survey 1:10,000 maps was divided into four 500m x 500m squares and a sample point marked at the centre. Samples were collected as closely as possible to each plotted point. However, in some cases the site was moved to the nearest undisturbed ground to avoid buildings, roads, railways, rivers etc.

The method of soil sampling used was devised by researchers at the Environmental Geochemistry Research Centre for Environmental Technology, Imperial College, London. This involved taking samples within a two metres square. At each site two samples were collected using a "Dutch auger":-

1. A composite surface soil sample (0-15cm depth) was collected from 9 sites within the $4m^2$ grid.
2. A sub-surface sample (30-45cm depth) was collected from 3 sites diagonally across the $4m^2$ grid.

The samples were placed into Kraft bags and labelled with the appropriate number. Duplicate surface soil and sub-surface samples were collected every 10 sites for incorporation into a sampling and analytical control scheme.

5.4.2 Sample preparation and analysis

Samples were air dried, disaggregated and sieved. The surface soils were sieved at a standard -2mm and the sub-surface soils at -150μm in order to be consistent with soil data collected as part of the regional geochemical survey of the UK. Samples were then ground and a 12g sub-sample taken for X- Ray Fluorescence (XRF) analysis. Control standards were used to monitor drift and duplicate samples analysed to estimate the combined sampling and analytical error

. Elements determined by XRF (total determination) included titanium (TiO_2), manganese (MnO), iron (Fe_2O_3), magnesium (MgO), aluminium (Al_2O_3), vanadium (V), chromium (Cr), tin (Sn), antimony (Sb), barium (Ba), cadmium (Cd), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), selenium (Se), molybdenum (Mo), tungsten (W), and lead (Pb). Selected elements have been plotted (Figs 20-29) to illustrate the dispersion of a variety of Potentially Harmful Elements (PHEs) in the Borough.

5.5 Results

The range of element concentrations found throughout the Borough is given in Table 3 (opposite).

5.5.1 UK Guidelines for soils

Guidance on acceptable levels of contamination for a variety of uses has been produced by the Government's Interdepartmental Committee on the Redevelopment of Contaminated Land (ICRCL). The guidelines give a list of elements and two soil concentration levels as follows:

- A threshold trigger level, below which the soil may be treated as though it is uncontaminated.
- An action trigger level, above which some remediation is recommended.

For the inorganic elements listed in the ICRCL guidelines no action levels are quoted. The DoE recommends that professional judgement is used to assess the significance of values above the quoted trigger level. The range of some selected elements in soil, for the Borough, are compared to ICRCL trigger values opposite.

Table 3. Statistics for Wolverhampton soils

Element	Max Surface	Max S/surface	Min Surface	Min S/surface	Mean Surface	Mean S/surface	Median Surface	Median S/surface	Mode Surface	Mode S/surface
TiO_2	1234	15100	450	4400	736	7734	738	7700	751	7700
MnO	712	7400	37	300	128	1285	115	1100	98	900
Fe_2O_3	12090	199700	2260	23800	4764	51611	4430	47600	4110	40500
MgO	3300	3800	500	500	1286	1415	1300	1400	1300	1500
V	308	468	35	37	104	111	95	97	86	98
Cr	1297	362	39	34	100	93	83	85	85	76
Sn	332	265	2	2	28	25	17	13	8	7
Sb	450	211	1	1	11	8	7	5	6	5
Ba	2399	2990	349	300	647	637	559	557	478	476
Cd	70	13	0	0	2	0	1	0	1	0
Co	89	104	6	6	20	21	17	17	15	14
Ni	264	345	12	12	42	43	33	35	23	30
Cu	3056	4414	14	11	141	141	79	71	46	31
Zn	7186	2500	61	51	488	377	279	243	144	119
As	157	178	3.5	7	20	20	17	16	13	15
Se	4	4	0	0	1	1	1	1	1	1
Mo	114	29	8	1	11	4	10	3	10	3
W	19	45	2	0	5	5	4.5	5	2	5
Pb	2853	1930	27	20	249	194	158	125	183	50

Element	ICRCL trigger level	Range in topsoils (ppm) (-2mm fraction)
As	$10^1/40^2$	3 - 157
Cd	$3^1/15^2$	0 - 70
Cr	$600^1/1000^2$	39 - 1297
Pb	$500^1/2000^2$	27 - 2853
Cu	130^3	14 - 3056
Ni	70^3	12 - 264
Zn	300^3	61 - 7186

[1] Levels for domestic gardens and allotments
[2] Levels for parks, playing fields and open spaces
[3] Anywhere plants are to be grown

It is recognised that there are a number of weaknesses in applying guidance values particularly as no common protocol is required for sampling and analysis. Guide values consider total determinations of contaminants not the 'availability' of that element to give rise to potential health effects or affect plant life.

5.5.2 Presentation of the soil data

Maps are presented which reflect the regional distribution of selected elements throughout the Borough. There are a variety of ways of presenting geochemical data and two methods are illustrated using point source and gridded data. In order to make a direct comparison the distribution of lead in the built environment (Figures 20 and 22) is shown using both methods.

In the gridded maps an attempt is made to construct a surface, the height of which is dependant on the element concentration at that point. The method uses a network of triangles in such a way that the vertex of each triangle is above a sample site at a height corresponding to its concentration. A different shape of network will be generated for each element. A mathematical formula is employed (a 5th degree polynomial) to make the surface smoother by changing each triangle from a flat face to a curved one which is fitted to the surface. Once a surface is generated it can be used to predict the element concentration at any point below it. Each grid cell on the map must be smaller than the inter sample distance (500m) and has been set at 250m for this application. Grid cells lying more than 1500m away from a sample point are given a null value and are not interpolated.

Point source data has been plotted for the remaining maps where the size of the circle is proportional to the element concentration. The key gives an indication of those values equivalent to current guidance trigger values, applicable to contaminated land, for reference.

The information shown on the maps of metals in soils does NOT indicate areas of either uncontaminated or contaminated land. They provide a guide to the distribution of metals over the Metropolitan Borough. The number of sample points is insufficient for assessing land as being either contaminated or uncontaminated. The maps indicate the probable estimate of soil quality interpolated over a wide area. For defined plots of land a detailed site investigation would be necessary to confirm the metal concentrations indicated by the maps.

5.5.3 Comparison with rural soils [Figures 20 and 21]

Comparing typical levels of heavy metals from the surrounding rural area with those within the Borough shows a marked increase for most metals coincident with the urban boundary. Both Pb and Cu show a marked increase over the rural background with higher levels being directly related to present or past industrialisation. Lead (Figure 20) shows a range of levels between 1 and 110ppm in the rural area compared to 36 to >710ppm in the urban area. Similarly copper (Figure 21) shows a rural range of 1 to 56ppm compared to an urban range of 19 to >530ppm. This pattern is not unique to Wolverhampton but can be observed for most built areas.

5.5.4 Lead (Pb) in surface soils [Figure 22]

Health effects

There is no evidence that lead plays any essential role in animal or plant nutrition.

Lead appears to exert little toxic effect on plants. It is, however, toxic to most animals, mainly by affecting the excretory organs. There is also evidence that suggests exposure of children under seven to even quite modest amounts of lead can, in the long term, permanently impair mental functions.

Distribution

In non-industrial urban areas the distribution of lead can be directly related to traffic movement where elevated levels in soils are found adjacent to major junction and roundabouts. In Wolverhampton the distribution of lead in soil cannot be attributed to traffic alone as the main influence is from the effect of both past and present industrial processes. When the dispersion of lead is examined with the aid of the land use maps it can be seen that the higher levels of lead (Figure 22) are consistent with known industrial areas or sewage treatment plants. The most marked dispersion of potentially higher values can be traced from the Springfield area towards East Park and into Bilston.

Only 8% of the data falls above the ICRCL trigger value of 500ppm for domestic gardens and allotments and less than 1% is above the 2000ppm trigger level for parks, playing fields and open spaces.

5.5.5 Lead (Pb) in sub-surface soils [Figure 23]

Overall Pb shows some attenuation with depth particularly over the less industrialised area to the west coincident with the main Triassic aquifer. However over made ground, mainly in the south east, values are variable and in some cases the profile levels are greater than the topsoil values suggesting an input from past industrial activity.

5.5.6 Copper (Cu) in surface soils [Figure 24]

Health effects

Copper is essential to the proper functioning of a wide variety of enzymes in both plants and animals. In plants, deficiency causes disorders of bark, shoot tips, stem form and elongation, bud formation, and leaf formation and form. Flower colouration is often badly affected, and grain and legume pods will fail to fill. Tomatoes suffer from a form of blossom end rot in copper deficient media. In grazing animals, the main diseases are hypocuprosis, which is caused by malfunction of a Cu-based enzyme in the liver, and spinal deformations known as swayback or swashback. In man, there are rare genetically induced Cu-deficiency disorders resulting in unusual hair growth, and loose skin. Dietary deficiency results in poor blood function and anaemia, and bone demineralisation.

There seem to be no diseases directly attributable to excess of copper in the diet, beyond a very rare form of hereditary toxicosis (Wilson's Disease) in which Cu accumulates in the tissues in man. It is known, however, that high levels of copper in the water supply can cause severe gastric irritation and anaemia. Likewise, there have been rare reports of fibrous lesions in the lungs of vineyard workers which is thought to be due to the use of Cu-based sprays, but such lesions are not reported in copper miners. Ingestion of extremely large doses of Cu causes kidney and liver failure. More relevant perhaps, is the suggestion that diets marginal in copper, but high in zinc, result in predisposition to ischaemic heart disease in man.

Dispersion

The distribution of Cu in the Borough is very similar to that of Pb although the higher levels are more restricted to the area immediately east of the city centre. This further confirms that the main source is related to past or present industrial processes.

Approximately 30% of the data falls above the ICRCL trigger value of 130ppm for any location where plants are grown.

5.5.7 Zinc (Zn) in surface soils [Figure 25]

Health effects

Zinc is an essential component of enzymes involved in photosynthesis, nucleic acid chemistry, protein utilisation and phosphorus chemistry, in both plants and animals. In plants, the most characteristic feature of a lack of Zn is leaf malformation and discolouration, although poor bud formation, poor flower production and fruit and seed production are all common symptoms. There are also considerable changes in the internal chemistry of fruits, particularly with respect to the forms of nitrogen present. In animals, Zn deficiency leads to loss of appetite and hence poor growth (dwarfism), sexual immaturity and, very typically in man, severe skin disorders. Effects on the immunosuppressive system have also been reported.

High concentrations of soil Zn are known to be phytotoxic, probably by interference with nitrate reductase enzyme and ATP enzymes. In animals the most important effect of excess zinc is severe anaemia, and complications arising there from. Excess zinc has also been implicated in the onset of oesophageal and stomach cancers.

Dispersion

Again Zn shows almost identical patterns to Pb and Cu although the dispersion associated with a sewage treatment plant in the north west is more pronounced. Approximately 52% of the data is above the ICRCL trigger value of 300ppm for any location where plants are grown.

5.5.8 Arsenic in surface soils (As) [Figure 26]

Health effects

There are no known diseases or disorders of plants or animals attributable to dietary deficiency of arsenic.

Arsenic appears not to be injurious to plants, although it commonly occurs with other elements that are e.g. high levels of sulphur, lead, zinc, copper etc. The element is one of the oldest poisons known to man and is equally toxic to most animals. The accumulation of arsenic in plants is thus a risk to man through the food chain, as is the contamination of water supplies. Excess of arsenic in the diet can cause severe skin problems, including cancer, and similar problems can occur from exposure to As-contaminated water. Chronic exposure to low doses of arsenic may lead to the development of lung and skin cancer. Arsenic is a severe intracellular toxin, and also causes serious peripheral vascular disease. Potential health risk associated with exposure to arsenic contaminated soil have been assessed (Murphy and Toole, 1989) in mining and smelting communities in the north-west USA where soil is contaminated by mill tailings and waste rock and also by wind carried smelter emissions.

Dispersion

Arsenic pattern are very similar to those for Cu, Pb and Zn and are thought to be related to a variety of industrial processes and sewage treatment plants.

Relating the levels to the ICRCL guidelines shows that 96% of the data falls above the 10ppm threshold value for domestic gardens and allotments but only 3% falls above the 40ppm level for parks. playing fields and open spaces. The validity of the lower trigger level must be questioned as soils in many parts of the UK exhibit natural background values well above 10ppm.

5.5.9 Cadmium in surface soils [Figure 27]

Health effects

There are no known effects which can be attributed to dietary cadmium deficiency in plants or animals.

Cadmium appears to be injurious to plants, although the mechanism is not clear and is an accumulative toxin in mammals. Its principal action is to progressively, and irreversibly, impair kidney function, a secondary result of which is the development of hypertension. Very high levels of ingested Cd can also cause severe dislocation of calcium metabolism, leading to joint and bone problems. In addition, long-term exposure to cadmium dust is thought to be a factor in the development of lung cancer.

Dispersion

The pattern of cadmium dispersion can again be related to industrial sites and in particular a sewage treatment plant. Approximately 10% of the data falls above the 3ppm threshold value for domestic gardens and allotments and less than 1% falls above the 15ppm level for parks. playing fields and open spaces.

5.5.10 Nickel and Vanadium in surface soils [Figure 28 and 29]

Health effects

Nickel tends only to be essential to plants when urea is the prime or only source of nitrogen available (either internally or as a fertiliser), as it is a component of urease enzymes. The plant group most affected is the Leguminocea. In animals (including man), low Ni diets produce symptoms of liver function impairment, poor iron metabolism and complex symptoms of enzyme malfunction including growth, hair and blood disorders. However, the precise mechanism of Ni function in animals is uncertain.

In plants, Ni toxicity results in characteristic development of white stripes on leaves, often in an oblique pattern, and can induce Mn deficiency in potatoes. In animals, excess nickel causes impaired liver function, and has been implicated in cancer formation, especially of the lungs of people who smoke.

Distribution

There is a clear relationship of relatively higher levels of Ni in areas of made ground, particularly in the south east of the Borough. This reflects the distribution of coal ash and slag present over the former coal mining area. A similar pattern is seen in the distribution of vanadium (Figure 29).

5.6 Surface water

A total of 223 samples of stream and canal water were collected within the Borough. Results of the survey are to be published in a separate technical report. At selected sites waters and bottom sediments and muds were collected to determine the level of the Polycyclic Aromatic Hydrocarbons (PAH).

5.6.1 PAH in the environment

Polycyclic Aromatic Hydrocarbons form a group of compounds which is almost ubiquitous in the environment. They are produced both by natural processes and also through anthropogenic activities. There is concern about the levels at which they occur both due to their toxicity and possible carcinogenic properties.

PAH are formed during pyrolysis and incomplete combustion of organic matter. They occur naturally in coals and oils as a result of burial processes, and in peats and soils as the result of wild-fires, and also by bacterial action. Anthropogenic PAH are introduced into the environment as a result of petrochemical processing, stubble burning, soot from chimneys, and as a consequence of the use of the internal combustion engine, in that PAH are present in exhaust fumes, sump oil and diesel fuel. Very little work has been carried out to discriminate between natural and anthropogenic PAH.

PAH are a large group of compounds, individual members of which are classed as toxic, irritant, mutagenic, carcinogenic or teratogenic. As a result of these properties specific PAH appear on the EC Priority List of Pollutants. They are also US EPA-listed and also are amongst the WHO list of "Compounds Hazardous to Health".

PAH are strongly hydrophobic and will sorb onto particulate matter (especially organic particulate matter) from water. Despite this limited solubility, low levels in drinking water can occur both as a result of PAH in the original source of the water and also due to constant leaching of PAH from the pitch used to line water supply mains in many areas of Britain. The latter source is expected to become less important as materials used for constructing the national network are replaced.

The survey of dissolved PAH in surface waters in the Wolverhampton area showed very low levels. This is not unexpected since streams, rivers and canals contain plenty of particulate matter onto which the PAH is able to sorb. The technique used in this study is not suitable for determining PAH at levels found in drinking water, but is suitable for waste waters and effluents. If the levels had been significantly high they would have been detected.

The determination of PAH in sediments from the Wolverhampton area is currently in progress, and will be published in a separate Technical Report (WI/95/15).

Total organic carbon (TOC) content was measured in the sediments collected. The TOC values ranged between 0.3% in the sandy sediment obtained from a drainage ditch, to 27% in sediment from the Staffs and Worcs Canal.

5.6.2 Oil in the environment

Oil-type hydrocarbons enter the environment in many different ways from both anthropogenic and natural sources. Natural sources are mainly oil and tar seeps, but recent organic matter from plant and animal debris can include hydrocarbons which may be difficult to distinguish from oil hydrocarbons (either natural or anthropogenic). Anthropogenic sources, which are very varied, include, vehicle and industrial emissions, road run-off, industrial and sewage effluents and grease and diesel from boats on canals and rivers.

The method of determining oil hydrocarbons in the sediments from the Wolverhampton study produces a pattern (or 'fingerprint') of the hydrocarbons present in the sample. This can then be interpreted by an experienced scientist, using comparisons with 'fingerprints' produced from known sources.

The canal sediments all show biodegraded oil fingerprints with the maximum concentration occurring in the carbon number range C20 to C27. This type of pattern is produced by bacterial activity on sump-oil, light crude oil or general road run-off. Some of the samples also show biodegraded diesel, characterised by hydrocarbons in the carbon number range C10 to C24, and peaking around C15.

The stream sediments all had a biodegraded diesel-type signature. Some also had a biodegraded oil pattern similar to that in the canal sediments, possibly due to road run-off. There were a number of samples which displayed alkane patterns similar to those shown by extracted plant waxes, resulting from the incorporation of recent organic matter into the sediment. A certain amount of plant waxes would have been extracted out of any plant remains present by the solvent used to extract the oil hydrocarbons from the sediment. One of the samples had a much lesser degree of biodegradation than was apparent in the rest of the stream sediments, this could be due to its location 50m downstream of a sewage outfall which would provide a constant supply of 'fresh' oil.

One sample had been collected from a pond whose source was in a landfill. This sample had a relatively pristine oil profile with little or no biodegradation. There were other components present, which could not be identified but which were probably derived from the landfill.

Oil hydrocarbons were not determined in the water samples collected as part of this study.

5.7 Gases

5.7.1 Soil Gas Sampling

At approximately fifty percent of the soil sites measurements were taken to assess the concentration of methane (CH_4), carbon dioxide (CO_2), and radon (Rn).

A hollow spike was driven into the ground at each location using a manually operated piston hammer. After sufficient depth was reached (c. 0.5 metre) the hammer was removed and an adapter fitted to the hollow spike. Soil gas was then pumped from depth into the measuring apparatus.

Methane, oxygen and carbon dioxide were measured using an Analox gas analyser. Radon and thoron measurements were collected using a Pylon AB-5 radon monitor to establish, the concentration of natural radionuclides within the underlying rocks and to identify any localised radioactive contamination. Gamma-ray spectrometric measurements were also taken using either an Exploranium GR-256 gamma-ray spectrometer or total gamma-ray rate meter. These systems can identify any artificial radionuclide component.The results recorded as percentages of the whole sample were refined to means for each rock type. For carbon dioxide positive measurements were gathered at each location. However methane was only detected at 15% of the sites making correlation to rock type or soil difficult.

5.7.2 Methane

Methane is a colourless odourless flammable gas, it is the most abundant organic chemical in the Earth's atmosphere. The nature, origins, occurrence, hazards, detection and monitoring of methane gas have been extensively reviewed in a CIRIA report (Hooker and Bannon, 1993). The greatest hazards posed by methane are fire and explosion.

The commonly perceived consequences of methane emissions for man, animals, vegetation and structures in the UK have until relatively recently been thought to have been restricted to the coal mining industry. Most people are aware of miners in the past using canaries in coal mines to detect 'mine gas' of which methane is a major component. The risks of methane and other gases in coal mining are well documented and controlled by legislation. Recently, there have been some tragic accidents involving methane outside coal mines that have brought to light the potentially dangerous nature of this gas in the environment. Methane becomes a problem if it is allowed to accumulate in a confined space such as a building or tunnel because at certain levels it forms an explosive mixture with air. Any source of ignition, electric lighting for example may trigger a fire or an explosion. Sixteen people were killed in an explosion whilst attending a demonstration of the new water pumping station at Abbeystead, Lancashire in 1984. Investigations showed that naturally generated methane had seeped into an underground water transfer tunnel and entered the valve chamber where it ignited when a cigarette was lit (Health and Safety Executive, 1985).

Methane is classed as a low toxicity gas but can be a simple asphyxiant due to the displacement of oxygen. Methane can also produce oxygen deficiency in the root zone of plants leading to the death of plants.

5.7.3 Sources of Methane

Sources and generation of methane in various environments are reviewed in detail in the CIRIA report (Hooker and Bannon, 1993). Methane abundance in the Earth's atmosphere has been increasing since the Industrial Revolution. Methane is formed by biogenic and inorganic processes in a number of natural and man-made environments. In the UK the alteration and breakdown of organic matter are the predominant sources of methane in the environment. In the urban environment the most likely natural sources of methane include, coal seams, oil shales, carbonaceous rocks, peaty soils, organic rich sediments and marshes. Important man-made sources include landfill sites and waste dumps as the biodegradation of waste can liberate methane.

5.7.4 Levels of Methane

Only a few positive readings were evident from the survey over the whole of the Metropolitan area and no obvious correlation with the geology was made. Elevated levels are anthropogenic in origin and are mainly associated with areas of landfill.

5.7.5 Carbon Dioxide

Carbon dioxide is colourless, odourless, toxic and asphyxiating gas which occurs in concentrations higher than in the normal atmosphere usually as a result of oxidation or combustion of organic materials or from respiration. There are a number of situations were CO_2 in the ambient atmosphere may differ considerably from that of normal air. This may be due to the incursion of CO_2 from an external source or due to the removal of oxygen. The result may be an atmosphere that is asphyxiating or toxic. Carbon dioxide is a respiratory and central nervous system stimulant at high concentrations but may produce unconsciousness and death at very high concentrations. The long term exposure limit (LTEL) is based on an 8 hour reference period, and the short term exposure limit (STEL) is based on a 10 minute reference period. CO_2 is classed as a highly toxic chemical. Exposure limits for CO_2 are 8 hours at 0.5 % vol and 10 hours at 1.5 % vol. The high solubility of CO_2 results in rapid diffusion and physiological effects are almost instantaneous. If elevated CO_2 concentrations are accompanied by reduction in oxygen concentration the effects will be more severe. Up to 10% CO_2 there are no permanent effects and individuals will recover with the administration of oxygen. Carbon dioxide is also associated with vegetation die-back in areas surrounding landfill sites (Barry, 1986).

5.7.6 Sources of CO_2

Carbon dioxide is the natural product of the indirect or direct reaction of organic materials with oxygen. The atmospheric concentration of carbon dioxide has increased from 280 ppm to 360 ppm over the last 100 years causing concern over global warming due to its effect as a greenhouse gas. Natural sources of CO_2 include animal and plant respiration which produces the majority of CO_2 in the atmosphere and bacterial activity which controls the amount of CO_2 in soil gas. The CO_2 content of soil may sometimes be 10 to 100 times higher than air in the associated atmosphere. CO_2 is highly soluble in water and CO_2 dissolved in ground water can be liberated from solution with pressure release. CO_2 can occur in organic rich or carbonaceous rocks and sediments and is generated by the oxidation of coal. CO_2 can also be generated in marshy and peaty ground and wetlands. The action of acid rain or groundwaters on carbonate rocks such as limestones can also liberate CO_2. Anthropogenic sources of CO_2 include landfills and waste sites as the biodegradation of waste liberates CO_2. Motor engines, coal fired power stations and other industrial processes also emit CO_2 into the atmosphere.

5.7.7 Levels of Carbon Dioxide

The highest measurements (of a mean exceeding 3% but less than 4%) were from soil gas collected in ground underlain by the Permo-Triassic beds to the west of the city which are predominantly covered by a sandy soil. The Carboniferous rocks to the east and south of the city area had measurements between 1.3% and 2.9% carbon dioxide of which the younger Clent Formation displayed the higher values. Elevated levels were not recorded from the Coal Measures.

5.7.8 Radon

Radon is a colourless, odourless naturally occurring radioactive gas that is produced by the decay of both uranium and thorium. In the past radon was regarded as harmless, being used in health spars. More recently its importance as the major contributor to the radiation dose received by the human body in the UK has been recognized. It disperses quickly in the open air but it can accumulate in buildings and mines where it is a potential health hazard. Much work into the effect of radon in buildings has been carried out by the National Radiological Protection Board (NRPB). The NRPB has advised the Government that radon concentrations above an action level of 200 becquerels per cubic metre of air should be reduced. An affected area is one where 1% or more of the housing stock are above the Action Level.

It has been shown (Clarke and Southwood, 1989) that at least 50% of the total radiation dose is from combined radon and thoron. The major pathway by which alpha particles (radiation) enter the body is by inhalation of radon and more importantly its immediate daughter products which also emit alpha particles. Most radon is breathed out again but the daughter products may remain in the respiratory system either in suspension as aerosols on dust and moisture particles. When ingested in the human body, alpha particles can give rise to tissue damage. The major health hazard from radon is thought to be an increased risk of lung cancer (Henshaw and others, 1990: O'Riordan and others, 1987).

5.7.9 Sources of Radon

Rocks that contain uranium and thoron, the parent elements of radon, provide a first indication of likely radon concentrations. Geochemical analyses of rocks and stream sediments in the UK have shown high uranium values associated with granites and certain types of mudstones and limestones (Ball and others, 1991). High uranium levels are also associated with some ironstones and sedimentary rocks containing uraniferous nodules. Mineralogical effects within rocks also determine the amount of radon produced, for example, the granites in south-west England generate more radon gas than the granites in Scotland due to different mineralogical effects.

5.7.10 Radon levels in Wolverhampton **[Figure 30]**

The nationwide survey of radon undertaken by the NRPB during 1992 shows that data for Wolverhampton are insufficient to make an accurate assessment. A total of 38 houses were measured in the Wolverhampton area and none was shown to be above the Action Level (200Bq/m^3), the maximum being 120Bq/m^3 and the remainder below 50 Bq/m^3.

The distribution of radon in the borough is shown in Figure 30. Low levels are expected over the Triassic rocks except where the Formation is overlain by glacial drift. The Coal Measures are classified as low with isolated highs due to the presence of uraniferous marine bands and an artificial permeability from the shallow mine workings. The area designated high overlies the outcrop of the Silurian limestone, in the south. In common with other areas of similar geology the limestones have a "high potential" for the emanation of radon. Faults shown (Figure 30) frequently emanate high levels of radon, either resulting from their increased permeability or from low level uranium mineralisation. The Borough is a low risk area for radon but indoor monitoring should be considered for houses built on the limestone in the south.

5.7.11 Background radioactivity

Results from the radiometric survey indicated background levels of gamma activity throughout the Borough from the sites sampled.

6. HYDROGEOLOGY

6.1 Introduction

The study area is one of moderate relief ranging between 100 and 200 m above OD. A watershed, trending approximately north-south through the Borough, separates the eastward-flowing headwaters of the River Tame (part of the Trent catchment), from the southwestward-flowing Smestow Brook system (part of the Severn catchment) (Figure 31). The largest river in the region, the Penk, rises outside the Metropolitan area, but a number of minor headwater streams have their sources within the Borough. This surface drainage pattern has been modified by the construction of the Staffordshire and Worcester, and Wyrley and Essington canals which cross the district.

Rainfall in the area is about 720mm per annum, spread evenly throughout the year. Potential evaporation is in the order of 490mm per annum; actual evapotranspiration is estimated to be slightly lower than this at about 470mm, of which about 85 per cent (400mm) is accounted for during the summer months. This value exceeds the average summer rainfall (360mm) and there is, therefore, usually no infiltration during the summer period. After evapotranspiration deficit compensation there is about 250mm per annum residual rainfall available for infiltration. However, the proportion of this reaching bedrock depends upon the nature of the soil and presence of drift cover and made ground.

6.2 Hydrogeological Database

Most of the water level and aquifer parameter data were obtained from the Hydrogeological Group of the BGS, whilst abstraction details were mostly supplied by the National Rivers Authority (NRA). In general, rest water level data are limited to those measurements made during construction of boreholes, and to occasional measurements subsequently. However, some additional water levels were measured during the water sampling programme for this study. Currently, only two sites are monitored routinely by the NRA. None of the existing abstraction sites has been geophysically logged. Some older abstraction data are also held by BGS since, under Section 6 of the 1945 Water Act (referred herein as Section 6 returns), total annual abstraction figures for boreholes were required to be sent to the, then, Water Department of the Geological Survey. After 1973, abstraction was licensed and all returns made to the local water undertaking.

6.3 General Hydrogeology [Figure 31]

Hydrogeologically, the Borough can be divided into three main aquifer systems (Table 4), which equate approximately with the Triassic, Permo-Carboniferous and Coal Measure sequences shown on the solid geological map. The Triassic Sandstone aquifer is the most important both in terms of its water-bearing characteristics, and in the quantity of water pumped for supply. Descriptions of the component formations in each aquifer are given in the Solid Geology section 3.3.

There is a widespread Drift cover (see section 3.6) but these deposits are of limited significance as groundwater sources, though they will influence aquifer recharge and contaminant migration.

Triassic Sandstone (major) Aquifer

The Triassic formations, together with the underlying Permian Bridgnorth Sandstone, are classified as a single unit for hydrogeological purposes. Although sedimentological differences between the individual formations can give rise to differing local conditions, the formations are considered to be in overall hydraulic continuity. Intergranular groundwater flow is important, especially where the sandstones are poorly cemented. However, the presence of fractures enhances the overall hydraulic conductivity of the aquifer and frequently contributes the bulk of the aquifer transmissivity. Mudstones and carbonate-cemented conglomerates are known to restrict vertical movement of groundwater, and this may result locally in significant vertical head differences within the aquifer. Where a borehole penetrates several formations, it is difficult to determine the proportion of water each formation yields.

The *Bridgnorth Sandstone* is a poorly cemented, well-sorted, medium to fine-grained sandstone, having a relatively high matrix permeability. The formation does not crop out in the Wolverhampton area, but has been proved at depth in a few boreholes in the west of the Borough. The lower 56m of the Tettenhall Borehole [8837 0009] are assigned to this formation.

The *Kidderminster Formation* (formerly Bunter Pebble Beds) exhibits both vertical and horizontal anisotropy due to the highly variable nature of the component lithologies, which range from cobble conglomerate, through sandstone to mudstone. Groundwater transmission is mainly through fissures. Discontinuous mudstone beds may locally partition this aquifer.

By contrast, the overlying *Wildmoor Sandstone* is of more uniform lithology and exhibits a relative 3-dimensional isotropy. The prime water transmission is intergranular. The Wildmoor Sandstone is finer grained than the Kidderminster Formation, and consequently does not normally yield water as freely as the latter. Nevertheless, significant contributions are derived from this formation.

The *Bromsgrove Sandstone* is vertically anisotropic, with groundwater movement restricted by both more cemented zones and mudstone beds. As with the Kidderminster Formation, the greater proportion of flow is through fissures, and yields will depend on their size and frequency.

Table 4. Aquifer classification and properties

Aquifer	Component Formations	Porosity (%)	Permeability (m/d)	Transmissivity (m^2/d)	Specific Yield
Triassic Sandstone Aquifer[1]	Bromsgrove Sandstone	18-30	0.2-5	140	0.05-0.15
	Wildmoor Sandstone	20-30	0.2-6	30-900	
	Kidderminster Formation	20-37	0.5-12	30-900	
	Bridgnorth Sandstone	17-34	2.7 [3]	90	
Permo-Carboniferous Red-beds	Clent Formation	8-10 [2]	$<6x10^{4}$	-	-
	Enville Formation	18-21 [2]	10^{4}-0.1	30-170 (350)	0.1-0.2
	Keele Formation/ Halesowen Formation/ Etruria Formation	-	-		-
Coal Measures	Middle Coal Measures	2-9	10^{4} - 10^{5}	-	-
	Lower Coal Measures	-	-	-	-

1 Includes Permian Bridgnorth Sandstone
2 Includes measurements on borehole core from outside the study area
3 Arithmetic mean given as a few values were too extreme to make a range meaningful

Aquifer Parameters

The transmissivity commonly ranges from 450 to 900 m^2/d, but decreases in the more cemented Bromsgrove Sandstone, and where the aquifer is confined. Transmissivity has been measured by extensive pumping tests at Wolverhampton Electro-Plating [9181 0292], sited on the Bromsgrove Sandstone, from where an average value of 140 m^2/d was obtained.

The porosity of the Triassic sandstones is high; core samples of Wildmoor Sandstone from a borehole at Wightwick Manor [8701 9839] gave values averaging 27 per cent. However, porosities are lower in the more cemented Bromsgrove Sandstone (Table H1). The porous nature of the Triassic Sandstone aquifer produces high values for specific yield, typically in the range 0.05-0.15. Where the aquifer is confined, the coefficient of storage is in the range 10^{3} to 10^{4}. The permeable nature of these sandstones permits substantial well yields of around 40 l/s on average, although some exceed 60 l/s. Well drawdown is typically in the range 15 to 40 m.

Groundwater Levels

Data on groundwater levels are sparse and it is possible to draw water level contours only in the south-western corner of the Borough (Figure 31). In the north and north-west of the area, the water table appears to be largely horizontal at around 105m AOD, although there is a slight gradient to the north-west. The River Penk appears to act as a hydraulic sink or line of groundwater discharge. The flat potentiometric surface in that area indicates a high transmissivity. Seasonal fluctuations of the rest water levels are mostly less than one metre, reflecting the high specific yield of the formation. These fluctuations are likely to be greater where the porosity is lower, as, for example, in the Bromsgrove Sandstone. In the past, some boreholes have been artesian (that is their piezometric head in the confined aquifer was above ground level), but over-exploitation earlier this century has led to a lowering of ground water levels. In recent years, groundwater abstraction has been reduced in most areas and, as a consequence, groundwater levels have largely recovered to those levels that existed at the turn of the century (see Section 6.6).

Abstractions

Public water supplies are licensed to abstract 2040 Ml/a within the district, and licensed industrial abstraction is set at 11570 Ml/a, giving a total licensed abstraction from the Triassic Sandstone of 13610 Ml/a. Statistics produced by the NRA for the period 1983 to 1992 show that actual abstractions for industrial and manufacturing purposes have fallen within the urban area from about 1600 Ml/a in 1983 to about 200 Ml/a in 1992, whereas public water supply abstractions (taken largely from outside the urban area) have shown a rough constancy over this same period at about 8500 Ml/a. Surface water total abstractions (mainly from canals) have shown a marked increase from about 700 Ml/a in 1983 to over 1600 Ml/a in 1992.

Permo-Carboniferous Redbed (Minor) Aquifer

This aquifer comprises strata from the top of the Productive Coal Measures to the top of the Clent Formation. The sequence, which is composed predominantly of red-beds, is up to 700 m thick, and comprises a laterally variable sequence of mudstones, sandstones and conglomerates. The Clent and Enville formations provide water for industrial use, and were formerly exploited for public supply at Goldthorn Hill Pumping Station [9102 9670]. Fractures are considered to contribute the bulk of the aquifer permeability. Porosities in the range 10-20 per cent have been determined on rock core samples from other areas (Table 4) but no porosity data exist for samples from the Wolverhampton area.

Abstraction

Yields obtained from this multilayer aquifer are very variable, but can be locally important. Using data from the BGS Well Archive, the average well depth is about 100 m, with a range of between 60 and 130 m. The mean yield is 7 l/s and the maximum is 18 l/s, with an average drawdown of 25 m. Water quality and composition are comparable to that of the overlying Triassic aquifer.

Coal Measures (minor) aquifer

Groundwater is mostly restricted to the sandstone beds, and this gives rise to a multilayered aquifer interspaced with aquitards of mudstone and claystone. The sandstones are mostly well-cemented, and intergranular porosity is very low. Due to the lateral impersistence of the sandstones, resources can be limited and recharge may be restricted through the intervening clay and mudstone layers. In their undisturbed state, these strata would provide very limited quantities of water from fracture systems developed in a relatively impermeable rock matrix (Table 4). However, as a result of extensive coal seam removal, the fracture density has been greatly enhanced and this has allowed a locally extensive secondary permeability to develop. This is evident in the large quantities of mine drainage water discharged in the area; one shaft (Bradley Mine [9568 9517]) pumped approximately 7Mm^3/a from 1948 to 1968, peaked at 8.9Mm^3 in 1959, and gave a 23 m drawdown at a pumping rate of 380 l/s.

Whilst coal mining was in operation, large volumes of generally poor quality mine water were pumped from mine workings to dewater the coal seams, but data concerning quantities, quality and discharge points of this water are not available.

Non-aquifers

Two areas of very low permeability rock are classed as non-aquifers.

i) In the extreme south is a small area of Silurian rocks. Limestones within this sequence may contain minor quantities of water, but the rocks are otherwise classed as impermeable.

ii) Dolerite intrusions within the Coal Measures are exposed in the central north-east of the district. Boreholes proving dolerite in the New Cross Hospital area either recorded no water, or water loss at the drift/dolerite boundary. As a result, the dolerites are likely, at best, to yield only very minor quantities of water.

Superficial (Drift) aquifers

The distribution and classification of the main drift deposits are shown on Map 12. In general, they are not a significant source of groundwater, although in the past small local supplies have been obtained from wells in glacial sand and gravel; Section 6 returns indicate approximately 30000 m^3/a were abstracted from 'Glacial Drift' for the years 1948-1964 at the Falcon Works, Wednesfield.

Glaciofluvial Sand and Gravel

Most of the mapped occurrences of glaciofluvial sand and gravel represent channel infillings cut into bedrock, and as such they are assumed to be in hydraulic continuity with the underlying solid formations. This is confirmed in the Dunstall area where, in both the Triassic sandstones and in the overlying channel sands, water levels are indistinguishable. Similarly in the east of the district, the buried Moxley Channel, although primarily filled with silty material, also contains sands and gravels, which may be in hydraulic continuity with the underlying Coal Measures. Such deposits can be expected to exhibit considerable intergranular porosities and high permeabilities.

Till (Boulder Clay) and Glaciolacustrine Deposits

In general, these deposits can be classed as poorly permeable (section 3.6). However the presence of impersistent sand and gravel lenses does lead to the development of localised perched water tables. Site investigation boreholes have shown that, in some areas in the west of the Borough, the piezometric surface of the Triassic aquifer lies within the till, so upward leakage from the Triassic sandstones into sand lenses within the till can occur. The low permeability of the till restricts infiltration to the underlying aquifers and provides some protection (of the aquifer) against pollutant migration from the surface (see next section).

Alluvium

The Alluvium forms very narrow strips in the floors of the stream valleys and is not considered to be of any hydrogeological interest.

6.4 Aquifer Vulnerability [Figure 32]

The vulnerability of an aquifer to pollution is an assessment of the ease with which contaminants can migrate from the surface to the saturated zone of the aquifer. The presence of any drift deposits overlying the aquifer may reduce its vulnerability to pollution, particularly where such deposits include relatively low permeability lithologies, such as till. Vulnerability maps produced for different parts of the UK differ in their treatment of the drift cover. For example, maps of vulnerability to nitrate pollution for the Severn-Trent region (Soil Survey and Land Research Centre, 1987) subdivided the aquifer on the basis of whether till cover was absent, thin and patchy, or contained in excess of 3 m of clay. In contrast, the NRA Groundwater Vulnerability maps for this region only indicate areas of reduced vulnerability where low permeability drift deposits overlie major and minor aquifers. In other regions, the presence of a drift (clay) deposit in excess of 5m in thickness has been used to indicate a lower vulnerability. However, even thicker clay layers, where they are fractured or weathered, may not provide adequate protection.

In the vulnerability map produced for this study (Figure 32), a 4 m cover of till has been taken as the nominal minimum thickness necessary to provide a degree of protection. It is clear from the map that, on this definition, most of the Triassic and Permo-Carboniferous aquifers, including the nominal 1km radius protection zone around Tettenhall pumping station, are highly vulnerable to pollution. It must be stressed, however, that the map is intended only as a guide to aquifer vulnerability; it takes no account of compositional variations within the till (e.g. sand lenses), or of structural weaknesses (e.g. fissuring) which will increase the permeability of the deposit and reduce its overall level of protection. The Tettenhall Pumping Station, for which Severn Trent Water plc hold the abstraction licence, is now used only to supply non-consumption uses at a local brewery. The 1km radius protection zone around this site is arbitrary and provisional only. The protection zone has not yet been formally defined by the EA but is scheduled for the next round of source protection zoning contracts (collectively known as GPZ3) which will start in early 1996.

6.5 Perched Water Tables [Figures 33,34]

Evidence from the many shallow site investigation boreholes drilled throughout the Borough suggests that perched water tables are widely developed within the drift sequence. In the north-west (Pendeford area), for example, the Triassic sandstone water table is at about 101m AOD but the till shows a perched water table at around 108m AOD (1973 figures). Although it is not possible to predict exactly where perched water tables will develop, their likely distribution can be gauged from geological considerations. The areas considered most at risk are those where (i) thick, relatively permeable made ground overlies clay-rich till or mudrock (Figure 34b), or where (ii) the glacial sequence is thick enough (over 4 m say) to include significant sand layers. The areas in the Borough where these conditions are satisfied are highlighted on Figure 33. The former coal-mining areas in the south-east of the Borough are clearly at risk, with colliery waste (up to 20 m thick locally) resting directly on thick till deposits. The quality of any water held in this sequence is likely to be poor, being high in sulphate, chloride, iron and manganese, with low pH values. Other areas at risk include Bradmore-Merry Hill, Fordhouses, Springfield and West Park, all of which are underlain by thick drift sequences.

Where perched water tables are present, seepages or small springs are liable to develop at the junction with less permeable strata (e.g.

where made ground thins against till). There may also be seepage to the underlying aquifer if the till itself thins or becomes more permeable.

The nature of perched aquifers is such that they are generally localised and ephemeral, often disappearing during prolonged dry periods. However, in some circumstances, a perched water table may persist throughout the year, particularly if it is being recharged by upward seepage of ground water from a partially confined (Triassic) aquifer.

6.6 Effects of Urbanisation on the Groundwater System

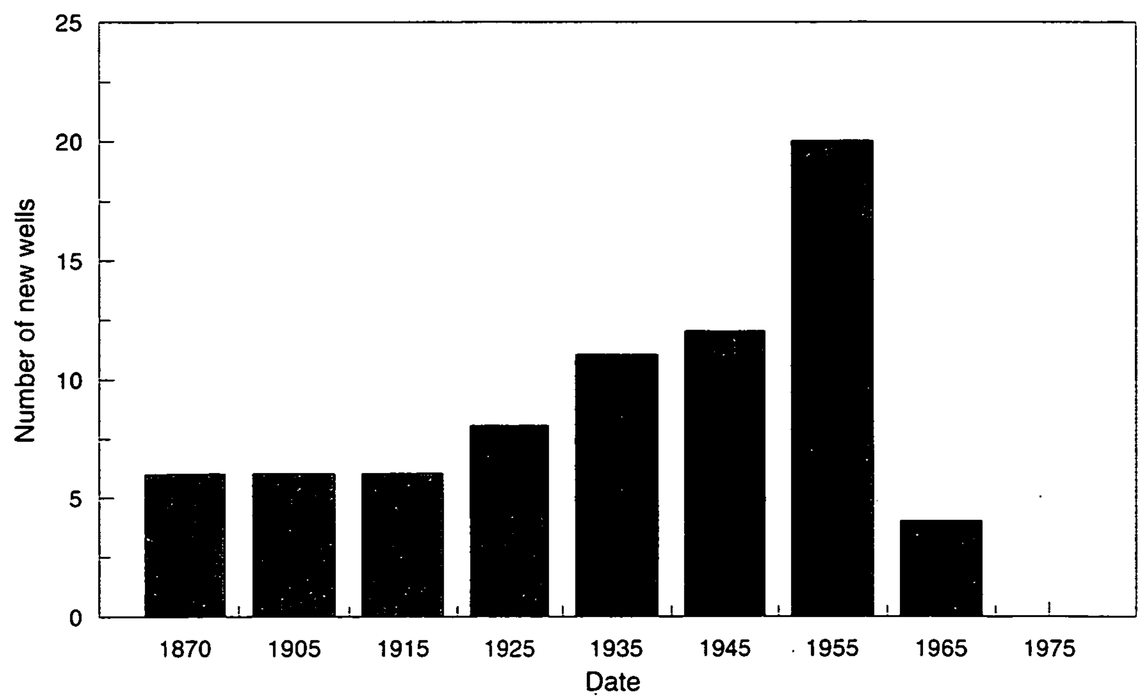
This section describes how the groundwater system has been modified by urbanisation, and the impact this has had on the development of the aquifer for water supplies.

Changing groundwater levels in the Triassic Sandstone and Permo-Carboniferous redbed aquifers [Figures 7, 34, 35, 36]

At the turn of the century, groundwater levels beneath the present day Metropolitan area were generally within 10 m of the surface (Figures 7, 34a). Abstraction at that time was quite limited and groundwater levels then probably represented the `natural aquifer condition'. During the following decades, increased industrial development and the ever rising demand for water led to a lowering of the groundwater levels beneath the Borough by up to 40 m. Whilst there are no figures available for the changes in the quantities of water pumped, an indication of the increase in abstraction can be gained from the frequency of sinking of new boreholes, which reached a peak between 1930 and the late 1950s (Figure 35).

More recently, the closure of much of the heavy industry has led to reduced groundwater pumpage and a consequent rise or 'rebound' of groundwater levels to positions, that in the 1990s, are close to those observed at the turn of the century. Similar groundwater level rises have been experienced in Birmingham, London and Liverpool over the same period (Knipe et al. 1993). The `rebound' effect within the urban area is illustrated by two boreholes that have been monitored by NRA since 1973 (Figure 36); one is at Oxley Gas Works [915 005], the other at Oxley Sidings [904 013]. The latter commences in Bromsgrove Sandstone and terminates within the Kidderminster Formation; the former penetrates the Kidderminster Formation and the upper part of the Enville Formation, thus entering into the Permo-Carboniferous. The hydrograph record of Oxley Gas Works shows a recovery of 15 m for the period 1973 to 1986. During the same period, the groundwater level at Oxley Sidings showed a recovery of only 5 m. The difference in recovery rate is probably due to a mixture of the differing transmissivities of the aquifers being tapped and local abstraction pattern changes. In the longer and more detailed record from Oxley Gas Works, the drought of 1976 is not evident, being masked by the steep water table rise. However, following the stabilisation of the water table level in the late 1980s, the drought of 1991/2 is apparent. It is significant that where groundwater levels in the rural areas to the west of the Borough have been monitored, as at Codsall [8840 0370]

Figure 35. Frequency of sinking of new boreholes (1870-1975).



(Figure36c), they show no similar long term trend, probably because the pattern of abstraction outside the main industrial centres has not been drastically modified.

Changing groundwater levels in the Coal Measures in response to mining

There is little information on groundwater levels in the Coal Measures although limited historical records held by BGS indicate that water levels prior to development of the coal seams are likely to have been within 10 m of the ground surface. The working of coal seams down to depths of over 80 m below surface necessitated dewatering to depths of over 100 m (Figure 7, section 1). Dewatering allowed air into the previously saturated and anoxic strata within the mine workings, resulting in oxidation of pyrite and other sulphide minerals. Closure of the mines during the second half of this century and the cessation of dewatering has led to a rapid rise in groundwater levels. These rising waters bring into solution sulphide oxidation products to produce groundwaters with low pH values, and rich in chloride, sulphate, iron and manganese. Groundwater levels are now believed to be at, or close to, those that existed prior to mining operations, but a relative lowering of the land surface by subsidence over the mined area could result in localised flooding where such areas are depressed below the water table. It is important to remember also that the hydraulic characteristics of the mined strata are very different now from those prior to mining operations, and this makes prediction of the groundwater flow pattern practically impossible. Groundwater from the Coal Measures, possibly of poor quality, could discharge into surface streams via layers of enhanced permeability (abandoned workings) or via sandstone units which have suffered mining-induced fracturing and collapse.

Urban recharge

Urbanisation has a profound impact on the hydrology of a catchment as it always results in impermeabilisation of a significant proportion of the land surface and often necessitates the importing of water from outside the area. Thus urbanisation provides important changes to the groundwater balance both by replacing and modifying recharge mechanisms, and by introducing new discharge patterns due to abstraction (Foster, 1990). Mains water leakage, in particular, can have a significant impact on aquifers within urban areas and may become the single most important component of groundwater recharge. In the Wolverhampton metropolitan area, recharge from leaking water mains has been estimated at about 140 mm per annum (Table 5) based on an assumption that 25 per cent of the water in the mains system leaks and infiltrates to the aquifer. Whilst sewers may also leak, they generally do not contribute greatly to groundwater recharge as, unlike water mains, they are not pressurised. In areas of high water levels or perched water tables, groundwater may actually flow into the sewer system. However, where sewers do leak to the aquifer, this can have a negative effect on the groundwater quality (see below).

Table 5. Calculation of recharge from mains water leakage.

Volume of water circulating in mains water system	108 Ml/d
Assumed % volume leaking as groundwater recharge	25
Volume of infiltration [1]	27 Ml/d
Equivalent infitration	circa 140 mm/a

1 Over the Metropolitan Borough area (70 km²)

In an urban setting, precipitation falling on impermeable surfaces such as buildings, roads, footpaths and car parks, is diverted into drains, which ultimately discharge into streams and rivers. Where this results in a significant increase in stream flow, these surface water courses may become localised sources of recharge to groundwater, though this is difficult to quantify. One example within Wolverhampton where this situation may apply occurs where groundwater is pumped from a disused colliery shaft at a rate of 20000 m^3/d and discharged to a canal. This canal crosses the Triassic sandstone and may contribute recharge to the aquifer by seepage through the canal bed.

The net overall changes to the groundwater balance beneath Wolverhampton as a result of urbanisation are shown in Table 6. The figures suggest that there has been an increase in groundwater recharge. This increase in infiltration to groundwater together with the considerable decrease in groundwater abstraction within the Borough explains the rapid rise in groundwater levels observed.

Negative Consequences of Rising Groundwater Levels

Groundwater levels will continue to rise until a new equilibrium between recharge and discharge is established. Increased groundwater discharge can occur as:

i) Increased baseflow to streams

ii) Increased seepage to the surface, which may produce localised flooding

iii) Increased groundwater flow away from city (i.e. reversal of previous groundwater flow paths)

Groundwater levels in the Triassic and Permo-Carboniferous red-bed aquifers have probably stabilised although, given the limited water level monitoring data available, this is difficult to confirm. In the Coal Measures, there is an almost complete lack of water level data, and it is uncertain whether or not water levels will continue to rise.

Shallow groundwater levels are of concern because they can result in:

a) Leakage into basements and service ducts

At the British Steel seamless tube factory near Wednesfield, located on Coal Measures, groundwater is being pumped to lower the water table and prevent ingress of waters into the furnace flues. This demonstrates the very considerable rise in groundwater levels that has occurred in the Coal Measures within recent decades.

Given the very significant rise in groundwater levels beneath the city centre, basements or tunnels constructed 30-40 years ago, at a time when the water level was more than 30 m below ground level, may now be liable to flood. Areas at risk include the low lying areas close to the main river valleys where the water table is within 5 m of the surface in some localities.

Table 6. Changes to recharge following urbanisation.

Source of recharge	Natural system (pre-urban) (mm/a)	Urban system (mm/a)	Comments
Infiltration through permeable ground	120-250 [a]	80-160 [b]	Urban infiltration reduced by about one third as a result of impermeabilisation of catchment
Mains leakage	-	140	Assume 25% of water circulating in mains system infiltrates to groundwater
Infiltration from surface water courses	Unknown	Unknown but possibly significant given large volumes of water discharged to streams and canals	
Leaking sewers	Negligible	Leakage is low and much less than from mains water system as sewers not pressurised.	
Total	120-250+	220-300	

a Likely average range in infiltration to the Triassic Sandstone Aquifer; maximum infiltration, up to 250 mm/annum, is possible where sandstones outcrop, but drift cover may reduce this figure by 50%
b Impermeabilisation of the catchment (by buildings, roads etc) probably reduces infiltration by 33%

b) Localised flooding.

Incidents of localised flooding have occurred in the city. Waterlogging of gardens in the Bradmore district and flooding near West Park Hospital have been reported and occur in areas where groundwater levels in the Triassic Sandstone aquifer are within 5 m of the surface (personal communication, Mr Barrett, 1994, Wolverhampton Metropolitan Borough Council). In both these incidents seepage from the Triassic sandstone aquifer may be responsible. Elsewhere, flooding events do not appear to coincide with shallow Triassic groundwaters and thus other causes, such as shallow perched water tables or leaking water mains, may be responsible.

It is important to distinguish between flooding caused by (a) rising water levels in major aquifers (which is likely to be a long term problem) and (b) perched aquifers (where water tables may be ephemeral and flooding likely to be short-lived).

c) Detrimental physical effects on buildings/foundations.

Rising groundwater levels can cause problems of subsidence due to a reduction in the bearing capacity of some unconsolidated strata by saturation. In addition basement retaining walls and tanks can be damaged by increased lateral or uplift pressures due to rising water levels. These problems are likely to be restricted mostly to areas where a shallow water table exists within thick unconsolidated deposits. Buildings founded upon bedrock are not at risk.

d) Corrosion of concrete foundations.

Concrete foundations are susceptible to chemical attack by aggressive groundwaters especially those enriched in sulphate. Groundwater derived from the Coal Measures, which can contain in excess of 500 ppm sulphate, may pose a significant risk in this respect.

e) Contamination of surface water

The rise in water levels within the aquifers beneath Wolverhampton will ensure that groundwater makes an increasingly important contribution to stream flow. Where groundwater is of poor quality a deterioration of the quality of the surface water courses can be anticipated. Contamination of surface water may arise either where mineralised groundwaters, principally derived from the Coal Measures and enriched in sulphate and various metals, discharge into a surface water course, or where rising groundwater seeps into contaminated land, causing mobilization of various organics and metals, which subsequently inflow to streams.

6.7 Groundwater quality [Figures 37,38]

Groundwater quality was evaluated by collecting water samples from 17 water supply well sites scattered across the borough. Samples were analysed for major ions, trace metals, dissolved organic carbon, and chlorinated solvents; of these, the chlorinated solvents are particularly useful indicators of industrial contamination. The limited nature of the sampling programme in this study calls for some caution in the interpretation and extrapolation of the analytical results, but despite this some interesting trends can be discerned from the data.

For a broad overview of the groundwater chemistry results the samples have been classified by their location (urban/rural) and by their source formation. However, groundwater samples from the Coal Measures were only obtained from urban-industrial locations. The average determinand concentrations in groundwater from the rural Triassic sandstone aquifer are shown in Table 7. Comparative data for each of the urban aquifers are shown graphically in Figure 37.

Groundwaters in the Triassic Sandstone and Permo-Carboniferous Red-bed aquifers are generally of good quality and of broadly similar type (Figure 38). They are enriched in calcium bicarbonate, which suggests that dissolution of calcium carbonate cement in the sandstones is the main control on groundwater chemistry. Groundwaters within the Coal Measure sandstones are, by comparison, more mineralised being enriched in sulphate and chloride (Table 8). The higher concentrations of the major ions relative to those in the rural Triassic groundwaters are thought to be due to natural geochemical differences.

Table 7. Average determinand levels in rural Triassic sandstone water.

	pH	DOC mg/l	SEC µS/cm	Na mg/l	K mg/l	Ca mg/l	Mg mg/l	HCO_3 mg/l	SO_4 mg/l	Cl mg/l	NO_3-N mg/l	Si mg/l	Li µg/l	B µg/l	Al µg/l	
Level	7.17	2.07	643.3	15.45	5.98	103.5	13.98	257.8	50.88	29.45	11.1	4.69	10.33	45.0	2.11	
Guide-line	5.5-9.5	n/a	1500	20	10	100	30	min 30	250	400	11.3	n/a	n/a	2000	200	
MAC				150	12	25000	50									
	Cr µg/l	Co µg/l	Ni µg/l	Cu µg/l	Zn µg/l	Ge µg/l	Rb µg/l	Sr µg/l	Mo µg/l	Cd µg/l	Sb µg/l	Cs µg/l	Ba µg/l	Tl µg/l	Pb µg/l	U µg/l
Level	0.4	0.36	5.04	4.8	11.91	0.03	0.8	97.30	0.3	0.04	0.07	0.0	178.58	0.02	0.9	1.41
Guide-line	50	3000		100	100	n/a	n/a	n/a	(70)			n/a	100	n/a		n/a
MAC			50	3000	5000					5	10		1000		50	

Guidelines are EEC, except where stated; MAC = maximum admissable concentration; n/a = not available; ( ) = WHO

Table 8. Major ion chemistry for the three aquifer units (mg/l).

	Na	K	Ca	Mg	HCO_3	SO_4	Cl	NO_3
Triassic Sandstones	12-28	2-16	80-165	7-32	200-370	25-110	21-72	2-24
Permo-Carboniferous Red-beds	11-54	6-12	92-210	20-33	320-360	30-200	26-135	2-22
Coal Measures	30-220	2-35	92-260	30-80	316-730	104-599	61-82	0.4-3

Impact of Urbanisation on Groundwater Quality

Urbanisation can have a major impact on groundwater quality, for example as a result of contamination from leaking sewers or long-standing industrial sites. Increased concentrations of boron, chloride and nitrate may indicate contamination by domestic wastewater and, by implication, sewer leakage. Industrial contamination may be indicated by increased concentrations of some metals, or more positively by the presence of synthetic organic compounds, such as chlorinated solvents.

i) Industrial Contamination

The quality of groundwater in the three urban aquifers (as compared with groundwater from a rural Triassic rural source) is illustrated in Figure 37. This shows enhanced levels of thallium, copper and antimony in samples collected from urban sites in the Triassic aquifer, suggesting that these elements are useful indicators of industrial contamination. In groundwaters from the Permo-Carboniferous aquifer, concentrations of cobalt, thallium, caesium and uranium significantly exceed those of the Triassic rural background. The uranium content may have a natural origin, since some marl bands in the Permo-Carboniferous have high gamma responses in geophysical borehole logs. Metal finishing is a major user of a wide range of heavy metals, and may be an important source of metal contamination in urban aquifers.

The Coal Measures groundwaters have much higher concentrations, particularly of boron, lithium, cobalt, rubidium, strontium and caesium, than those from rural Triassic sandstone sources, which is probably largely a result of natural geochemical differences. Comparable concentrations of zinc, boron and sulphate, as well as similar specific electrical conductivities, have been recorded in other British Coal Measures groundwaters by Younger (1993) and Aldous et al. (1986). In addition, Edmunds (1975) showed that Coal Measures groundwaters are significantly enriched relative to seawater in lithium, strontium, cobalt and caesium. Bonta et al. (1992) have demonstrated that coal mining activities can result in the release of significantly increased concentrations of natural contaminants in coalfield groundwaters, and this may have occurred in Wolverhampton. However, it is quite possible for the groundwaters beneath Wolverhampton to have been contaminated by coal ash waste which is also enriched in these elements (Carlson and Adriano, 1993; Simsiman et al., 1987).

Synthetic organic compounds, particularly chlorinated solvents, are much more useful indicators of industrial pollution since they are clearly anthropogenic. These solvents include tetrachloroethene, formerly perchloroethylene (PCE), trichloroethene (TCE), trichloroethane (TCA) and carbon tetrachloride (CT). These are widely used in the metal and engineering industries and PCE is also used in dry cleaning processes. In general, usage of TCE has declined in the UK due to its progressive replacement by TCA. In an urban area there are likely to be many sources of these contaminants.

These solvents were detected in the urban groundwater beneath Wolverhampton at fairly low concentrations, up to a maximum of 26 µg/l for TCE (Table 9), which is still below the UK guideline of 30 µg/l (Lerner et al., 1993). TCE was detected at concentrations above 0.1µg/l in more than 50 per cent of the boreholes sampled (Table 10), suggesting that contamination of the urban groundwaters beneath Wolverhampton by this solvent is fairly ubiquitous. Much of the contamination probably occurred prior to the 1980s, before TCE had been replaced by the other solvents. The samples were taken from pumped production boreholes, in which the precise depth of the screened portion of the borehole is, in many cases, unknown but likely to be of significant length. Such samples will therefore represent an 'average' or 'mixed' sample from the aquifer, and thus much higher concentrations may occur at discrete horizons. The relatively low concentrations of chlorinated hydrocarbons in groundwaters beneath Wolverhampton compare favourably to those found in the Permo-Carboniferous groundwaters beneath Coventry (Lerner et al., 1993), and in the Triassic Sandstone aquifer beneath Birmingham (Rivett et al., 1990). For example, in Coventry chlorinated hydrocarbon concentrations exceeded 1000 µg/l in pumped wells, whilst in Birmingham 40% of the 59 supply boreholes tested were contaminated by more than 30 µg/l of TCE, with a maximum concentration of 5500 µg/l.

Table 9. Range of concentrations (µg/l) of TCE in different aquifers beneath Wolverhampton.

Aquifer	Total number of samples	Number of samples with concentration (µg/l) of TCE in range:				
		<0.01	0.01-0.1	0.1-1.0	1.0-10	>10
Triassic Sandstone (Rural)	5	1	4			
Triassic Sandstone (Urban)	4			3		1
Permo-Carboniferous	4			1	2	1
Coal Measures	4		3		1	

Table 10 Range of concentrations of various solvents in groundwaters beneath Wolverhampton.

Concentration range (µg/l)	Number of sites			
	TCE[a]	PCE[b]	TCA[c]	CT[d]
<0.1	8	15	14	16
0.1-1.0	4	1	3	1
1.0-10	3	1	-	-
>10	2	-	-	-

[a] World Health Organisation (WHO) guideline value 30µg/l
[b] WHO guideline value 10µg/l
[c] WHO guideline value not stated
[d] WHO guideline value 3µg/l

It is interesting to speculate on the reasons for the differences in the solvent concentrations observed in Coventry and Birmingham on the one hand, and in Wolverhampton on the other. All three metropolitan areas are underlain by drift deposits of broadly similar thicknesses and distribution, so that the vulnerability to pollution is unlikely to differ significantly. The bedrock geology is also comparable. One possible explanation is that both Coventry and Birmingham supported major motor manufacturing plants and ancillary industries, involving a greater use of solvent than was the case in Wolverhampton. In addition, the studies in Coventry and Birmingham did include samples from production boreholes used by current major organic solvent users. In those sites in Birmingham, with no history of solvent use, groundwater concentrations of chlorinated solvents were found to be less than 50µg/l (Rivett et al., 1990).

The considerable rise in groundwater levels recorded beneath parts of the Borough of Wolverhampton may result in movement of water up into contaminated land beneath sites which have a long history of industrial use. Mobilisation of contaminants, including organic compounds and toxic heavy metals, is possible and could result in contaminant groundwater plumes moving off site to neighbouring boreholes or to surface water. Careful monitoring of water levels and quality is recommended especially around potentially contaminated sites.

ii) Leaking Sewers

Sewers which leak may well contribute to a deterioration of groundwater quality, both chemically and bacteriologically, although the significance of this problem in urban areas of the UK is largely unknown. In this study no bacteriological analyses were undertaken. However, the chemical indicators of domestic wastewater (boron, chloride and nitrate) were used to indicate groundwaters that may have been affected to some extent by sewer leakage.

The Permo-Carboniferous Red-bed groundwaters, which were all sampled from the urban section of the aquifer, show a strong positive correlation between the three ions indicating a linked source and therefore suggesting wastewater contamination (Table 11). In contrast, the Triassic Sandstone groundwaters show poorer correlation between chloride, boron and nitrate. This suggests that a single source is not responsible; since these groundwaters included samples from rural areas, a large proportion of the nitrate may be derived from agricultural sources. Further, the lower density of sewers in rural areas will ensure that sewer leakage is likely to have a lesser impact on groundwater quality. Results from the Coal Measures show strong negative correlations of both chloride and boron with nitrate, and low nitrate concentrations overall. This indicates that the source of chloride and boron is unlikely to be from domestic wastewater; but is probably from water-rock interaction as mentioned earlier.

Table 11. Correlation of sewage indicators for the three main aquifers.

	Triassic Sandstone aquifer	Permo-Carboniferous Red-bed aquifer	Coal Measures aquifer
	Rural/urban	Urban	Industrial
[1] R^2 Cl:NO_3	0.792	0.935	-0.874
R^2 B:Cl	0.620	0.969	0.868
R^2 NO_3:B	0.803	0.969	-0.966
Cl range (mg/l)	16.5-72.4	26.3-135	60.8-81.8
NO_3-N range	1.6-28.5	2.4-22	<0.4-3.2
B range (µg/l)	0-150	30-470	130-1000
Comments	Combined data for rural and urban sites. High NO_3-N from agricultural activity.	Cl, NO_3 and B all highly correlated most likely due to urban sewer leakage.	High negative correlations with NO_3 due to lack of NO_3 implying lack of agricultural and domestic sewer influences.
Number of samples	9	4	4

1 R^2 is the correlation coefficient; values that approach 1 indicate a high degree of correlation.

6.8 Conclusions

The Triassic Sandstone aquifer is the most important groundwater source in the Wolverhampton area. High matrix permeability coupled with extensive fissuring make it a highly productive aquifer.

The Permo-Carboniferous aquifer is also important and was used extensively to provide limited industrial supplies. Fractures contribute the bulk of the permeability of this aquifer. Originally the Coal Measures would have had a more restricted groundwater potential, due to pervasive cementation and intervening aquitards. The groundwater potential of the Coal Measures has largely been created by extensive mining, which has resulted in the development of a pervasive fracture system. Formerly, large volumes of water were pumped from this formation in order to dewater coal seams to allow mining access.

The overlying drift deposits are important for two main reasons. Firstly, for their influence on aquifer vulnerability to contamination, and secondly, because they may permit the development of perched water tables.

Groundwater levels within the urban area were significantly lowered earlier this century due to groundwater abstraction by industry and coal mine dewatering. Following the closure of many industries and mines, groundwater levels have largely recovered to those at the start of the century. Groundwater levels in some areas are very close to the surface and there is a need for improved groundwater monitoring to assess the situation thoroughly.

Rising groundwater levels are recognised as a serious urban problem and can cause a variety of hazards, including localised flooding of basements and low-lying areas, reduction of soil bearing capacities under foundations and the mobilisation of contaminants caused by saturation of contaminated land. This can lead to corrosion of concrete foundations and pollution of surface waters. These are issues for concern in Wolverhampton given the rapid rise of groundwater levels that has occurred beneath the Borough.

The water quality survey suggests that leaking sewers may have contaminated some of the urban Permo-Carboniferous groundwaters. Industrial contamination of urban groundwaters in all three aquifers is indicated by the occurrence of low concentrations of chlorinated organic solvents and the presence of some metals. However, despite a similar geological setting in Wolverhampton to that in Birmingham and Coventry, the level of contamination by chlorinated solvents is much less in Wolverhampton than in the latter two cities. This may be explained in part by the greater use of these solvents by industries in these cities.

Given the concern that rising groundwater levels may mobilise contaminants present in the subsurface, it is recommended that solid and water samples be obtained from cored boreholes drilled beneath long-standing industrial sites. These samples should be analysed for a range of organic contaminants including BTEX (compounds of benzene, toluene and xylene), phenols and chlorinated solvents.

7. CASE STUDIES

7.1 Case Study I: Contaminant migration beneath landfill and colliery waste at Bowmans Harbour

The current redevelopment of Bowmans Harbour [SO9389 9936] by the Black Country Development Corporation has provided an opportunity to study the effects of leachate contamination beneath a 30 to 40 year-old landfill site. The results of this investigation are described by Fenwick and Cave (1996) and only a summary of their report is given here.

Site History

Bowmans Habour was formerly a mining and metal processing centre. During its early history, over 100 shallow shafts were sunk within the site boundary to exploit the three main seams of the Fireclay Coal group, which subcrop beneath till cover. Spoil from these early workings was spread over most of the site to a depth of between 1 and 10 m. The site was subsequently used for waste disposal purposes. The oldest waste is made up of ash and burnt waste and probably predates the 1956 Clean Air Act. Later, during the 1960s and early 1970s, domestic refuse was deposited directly on top of the older waste with no form of liner or even basic levelling of the ground surface. This waste was left mainly uncovered until the present day. Remediation has involved relocating the domestic waste within a permanent till-lined repository.

Site Stratigraphy

The stratigraphy of the natural and man-made deposits at the time of this study is summarised below.

Domestic waste (1960s-70s) with some inert industrial waste	8-9m	A wide range of materials including paper, plastics, cloth, glass, rubble and decayed waste
Domestic burnt waste and ash (pre-1954)	1-1.5m	
Colliery spoil	1-10m	Seatearth, black carbonaceous shale and poor quality coal fragements, as well as some burnt material, soil and sand
Soil profile with C, B and sometimes A horizons		A horizon: as for B but dark grey in colour B horizon: cohesive, grey to grey-green silty clayey sand C horizon: loose yellow-grey to brown sand
Till	2.5-4m	red-brown structureless silty and clayey sand with sporadic pebbles
Productive Coal Measures		sandstone, mudstone, seatearth and coal seams

At any one point, only part of this succession may be present.

Hydrogeology

Natural Groundwater

The piezometric head at the site was originally predicted to be close to the ground surface, but after excavation commenced no real groundwater problems were experienced, even at the full depth of the excavation.

Leachate

Signs of leachate, in the form of fine orange rivulets, were seen running out of the base of the landfill, on the site visit of 30.3.94; there were also greater flows of clearer water at many locations. These derived from the base of the 1970s waste, where it rested directly on till. In the follow-up field sampling visit on the 2.10.94 there were few signs of leachate, there having been a drought all summer and only overnight drizzle as precipitation.

Sampling and Testing Strategy

Although it would have been preferable to study the migration effects of contaminants across the landfill/till boundary directly, site conditions on the day dictated that sampling had to be restricted to sections where domestic waste was separated from the underlying till by an intervening layer of colliery spoil.

Trenches were cut at two locations (A [393886 299353]; B [393900 299368]) exposing continuous sections through landfill, colliery spoil and into the till below (Figure 39). From each trench, bulk samples were taken of the colliery spoil, the soil horizons and the till beneath. The bulk samples were squeezed in the Engineering Geology and Geophysics Group laboratories to obtain pore water samples. These waters were then analysed for major and minor ions, a range of trace elements, as well as pH and total organic and inorganic carbon. Stiff plots showing the change in ionic concentration of the pore waters down each trench profile are shown in Figure 39.

Summary results

- The pore water samples are chloride rich with high total dissolved solids (TDS) levels.

- Both sites show an overall upward increase in the ionic content of the pore waters, implying contamination from above. However, at site B, TDS levels are higher overall indicating greater contamination penetration through this section. An explanation for this may be that both the soil profile and till at site B have lower clay and silt contents than at Site A, implying greater permeability.

- The chemical profiles show that most of the pollution appears to have been contained within the uppermost metre of till. However both Cl and Br, which are relatively mobile elements, are still significantly raised in the lowest till sample of the more heavily polluted section B (Figure 39).

- High levels of iron and manganese were found in the soil layer samples of both pits. These may relate to the metal working that was known to have occurred in this area before it was used as a landfill.

- Trace elements (Ni, Li, Zn) have their highest concentrations in the colliery spoil indicating derivation from this source or from the landfill above. Zinc, additionally has a concentration spike in the B horizon soil of Pit A, probably again related to former metal working.

Conclusions

The pore water chemical analyses have shown that contaminants can penetrate at least a metre into more sandy, weathered zones in Upper Devensian till. This is particularly the case for conservative ions such as chloride and bromide. Therefore caution and rigorous quality control over matrix and bulk permeability is needed when using this till as a landfill liner.
Although colliery spoil can be a source of contaminants in itself, its high carbon content may sorb many contaminants passing through it, and so could perhaps help to reduce and retard the permeation of contaminants from landfill waste overlying such colliery spoil. Since many unlined landfills overlie colliery waste in the Wolverhampton area, and probably over much of industrial Britain, this is an important factor to be considered, which deserves further investigation.

7.2 Case Study II: East Park, Wolverhampton - An Environmental Site Investigation

East Park [393 298], a recreational park situated to the south-east of Wolverhampton town centre has provided an opportunity to access and investigate the ground beneath an urban environment. The environmental site investigation of East Park has enabled the nature and spatial distribution of potential contaminants associated with the underlying strata and historical industrial land use to be examined. The results of the survey are detailed more fully in a separate report by Wealthall et al. (1995)

Site History

East Park was created in the 1890s on land reclaimed from a former colliery and iron and tool works. Much of the original land surface contained pit shafts, furnace ash and sulphurous coal dust. During construction of the park, which covers an area of approximately 20 ha, pit shafts were filled, and over half of the site, slag heaps were levelled. A 4 ha boating lake constructed in the park was found to leak continually as a result of poorly sealed pit shafts.
The park remains a recreational facility with the western half dedicated to sports fields and the eastern half to unlevelled but landscaped slag heaps which are covered by mature trees, grass and shrubs. The boating lake has now gone.

Site investigation

The overall purpose of the investigation was to assess the nature and spatial distribution of potential contaminants in the sub-surface, identify pathways for migration and potential environmental receptors. This has involved an integrated study of the geology, hydrogeology and geochemistry of the site.

A phased approach to the site investigation has been adopted (Figure 40) which has enabled a range of standard methodologies to be applied and compared. Initially, an extensive desk study was carried out to collate all the relevant historical and scientific information, before designing the field-based investigation and sampling strategy.

The desk study confirmed details of the sites history and provided an indication of the types of contaminants likely to be present (although others were not precluded). Geologically, the site was believed to consist of Made Ground overlying till, with Coal Measures beneath. Groundwater was known to be present in the Made Ground suggesting that the till was behaving as an aquitard. The desk survey also revealed the presence of external contaminative sources such as the nearby Stowheath landfill.

Three boreholes, spatially distributed across the site, were then drilled to confirm the geology, to provide sediment and groundwater samples for geochemical analysis, and to enable soil gas concentrations of methane, carbon dioxide and oxygen to be measured. In addition, a detailed soil gas spike survey and geochemical sampling programme were undertaken across the whole park.

Geology

The stratigraphy of the deposits beneath East Park determined from the drilling is summarised below.

Lithology	Thickness (m)	Description
Top Soil	0.2 - 0.3	
Made Ground	5.0 - 6.4	- disturbed clay material containing mudstone, shale, coal and sandstone clasts (spoil). - stiff grey clay - gravel and sand (slag)
Till	5.8	very stiff to soft, reddish brown sandy clay with sandstone greywacke and igneous clasts.
Coal Measures	unproven	Shale

Hydrogeology

In each of the boreholes drilled, groundwater was encountered within the Made Ground resting on top of till. The approximate depth of water was 2.8 m. In one borehole, a shallow perched water table was encountered in the Made Ground. The till was partially saturated and the Coal Measures unsaturated over the shallow depth penetrated. No clear indication of groundwater flow was possible but it is believed to be towards the south-west. Hydraulic conductivities of the made ground varied between 10^{-4} - 10^{-7} m/s, and those for the till between 10^{-7} - 10^{-8} m/s.

Groundwater chemistry results indicated that whilst the quality of water was not suitable for drinking water, the analyses did not indicate significant contamination. However, the potential for rapid movement of water through the made ground may result in significant dilution of potential contaminants at certain times and not at others. It is therefore recommended that temporal variation in groundwater quality be studied.

Geochemistry

Soil samples collected during the investigation were analysed by XRF, ICP-AES and ICP-MS to determine a wide range of elemental concentrations. The results indicated that the slag material of the made ground, which is generally found below 3.0 m depth, contained significantly elevated concentrations of trace elements including nickel, copper, zinc, lead and cadmium. Other components of the made ground showed variable concentrations of trace elements with arsenic, selenium, vanadium, chromium and barium all above natural background concentrations. The trace element analysis of the till revealed concentrations which were typical of background in this area indicating that no or very little vertical downward migration of contaminants had occurred at the sites investigated.

Gas surveying

Near surface gas (< 1.0 m depth) concentrations showed that carbon dioxide concentrations ranged between 0 and 8.4% v/v and oxygen between 11 and 21% v/v. Methane was found at only five of the 150 sites investigated across the park at concentrations of up to 3% of the Lower Explosion Limit (0.15% v/v).

Sampling from the borehole completions revealed a maximum carbon dioxide concentration of 13.2% v/v at a depth of approximately 5.0 m. No methane was detected in the boreholes.

Conclusions

- the application of standard site investigation methods and guidelines has been successfully applied within a clearly defined framework at East Park.

- the original conceptual model of a three-layered structure to the site was proven and refined.

- the made ground contains elevated concentrations of trace elements especially in the slag component. These elements reflect the historical industrial land use of coal mining and metal works.

- trace element concentrations in the underlying till reflect background levels for the area and so indicate that there has been no widespread vertical migration of the contaminants.

- only low concentrations of methane were found on the site indicating that no major source of this gas is present within the site boundary and there is no or very little migration of gas on to the site.

- although the quality of groundwater found in the made ground (which is not an exploited aquifer) did not satisfy drinking quality standards, no significant contamination was found. However, significant dilution of groundwater may occur as a result of rapid recharge and so temporal variations should be studied.

8. GIS CAPABILITY

[Figure 41, 42]

Thegeoscience information gathered in the course of the project has been integrated into a PC-based GIS running MapInfo software. A customised front end (Figure 41) allows point or Borough-wide searches on a range of themes, using National Grid Reference or postcode for location purposes. An example of the type of derivative map that can be produced within the GIS is shown in Figure 42, which shows the significance to planning and development of selected foundation conditions within the Metropolitan Borough.

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10 REFERENCES

ALDOUS, P J, SMART, P L, and BLACK, J A. 1986. Groundwater management problems in abandoned coal-mined aquifers: a case study of the Forest of Dean, England. *Quarterly Journal of Engineering Geology*, Vol. 19, 375-388.

ALLOWAY, B J. 1990. *Heavy metals in soils*. (Glasgow and London, Blackie.)

ANGINO, E E. 1970. Environmental geochemistry, politics, and reality. *Geological Society of America*, Abstract. Vol. 3, No 7, 493-494.

ASAMI, T. 1984. Pollution of soils by cadmium. *in* Nriagu,J O., Changing mital cycles and human health. *National Water Res. Insr., Environ. Can.*, 95-111.

BALL, T K, CAMERON, D G, COLMAN, T B and ROBERTS, P D. 1991. Behavior of radon in the geological environment: a review. *Quarterly Journal of Engineering Geology*, Vol. 24, 169-182.

BARLTROP, D. 1979. Geochemical and man-made sources of lead and human health. *Philosophical Transactions of the Royal Society of London*, Vol. B, No. 288, 205-211.

BARNHISEL, R I, and MASSEY, H F. 1969. Chemical , mineralogical and physical properties of eastern Kentucky acid-forming coal spoil materials. *Soil Science*, Vol. 108, No. 5, 367-372.

BARRY, D L, 1986. Hazards from methane on contaminated sites. *Proceedings of the International Conference on Building on Marginal and Derelict Land*, Glasgow, 7-9th May, 209-224.

BERROW, M L and BURRIDGE, J C. 1981. Persistence of metals in available form in sewage sludge treated soil under field conditions.(C.E.P. Consultants, Edinburgh.)

BONTA, J V, AMERMAN, C R, DICK, W A, HARLUKOWICZ, T J, and RAZEM, A C. 1992. Impact of surface coal mining on three Ohio watersheds - groundwater chemistry. *Water Resources Bulletin*, 28/3, 597-614.

BULLOCK, P and GREGORY, P J. 1995. Soils: A neglected resource in urban areas. *in* Soils in the Urban Environment (editors Bullock, P and Gregory, P J.) (Blackwell Scientific Publications.)

CARLSON, C L, and ADRIANO, D C. 1993. Environmental impacts of coal combustion residues. *Journal of Environmental Quality*, 22/2, 227-247.

CHARNEY, R L. 1985. Potential effects of sludge borne heavy metals and toxic organics in soils, plants and animals and related regulatory guidelines. *in* Report Workshop Int. Transportation, Utilization and Disposal of Sewage Sludge Including Recommendations. PNSP/85-01, Pan American Health Organisation, Washington, D.C; 1985: 1-56.

CHOW, V T. 1978. *Advances in hydroscience*,(New York, Acad. Press.)

CHU, W S. 1987. An evaluation of data requirements for groundwater contaminant transport modeling, *Water Resources Research*, Vol.23, No.3, 408-424.

CLARKE, R H and SOUTHWOOD, T R E. 1989. Risks from ionising radiation. *Nature*,338, 197-198.

DAVIES, B E. 1983. A graphical estimation of the normal lead content of some British soils. *Geoderma* 29, 67-75.

DAVIES, B E. 1978. Plant-available lead and other metals in British garden soils. *in* The science of the total environment, 243-262.

DAVIES, B E. 1980. *Applied soil trace elements*, (B E Davies, Editor). (Chichester, John Wiley and Sons Ltd.)

DEPARTMENT of the ENVIRONMENT. 1994. *Framework for contaminated land.*

EDMUNDS, W M. 1975. Geochemistry of brines in the Coal Measures of northeast England. *Transactions of the Institute of Mining and Metallurgy*, Section B, Vol. 84, B39-B52.

FENWICK, S M, and CAVE, M R. 1996. Contaminant migration beneath landfill and colliery waste at Bowmans Harbour, Wolverhampton. *British Geological Survey Technical Report*, WN/94/41.

FERGUSSON, J E. 1990. *The heavy metal chemistry, environmental impact and health effects*. (Oxford Pergamon Press.)

FORSTNER, U and WITTMAN, G T W. 1981. *Metal pollution in the aquatic environment*. (Berlin, Springer.)

FORSTNER, U and MULLER, G. 1973. Heavy metal accumulation in river sediments; a response to environmental pollution. *Env. Geol.* Vol.25,265-573.

FOSTER, S S D. 1990. Impacts of urbanisation on groundwaters. IAHS Publication, No. 198, 187-207.

HAMBLIN, R J O. 1982. Geological notes and local details for 1:10 000 sheet SJ90SE (Essington and Bloxwich). Keyworth, *British Geological Survey*.

HAMBLIN, R J O, and GLOVER, B W. 1991a. Geological notes and local details for 1:10 000 sheet SO99SW (Dudley and Sedgley). 2nd Edition. Keyworth, *British Geological Survey Technical Report* WA/91/72.

HAMBLIN, R J O, and GLOVER, B W. 1991b. Geological notes and local details for 1:10 000 sheet SO99SE (Dudley and Wednesbury). 2nd Edition. Keyworth, *British Geological Survey Technical Report* WA/91/73.

HAMBLIN, R J O, HENSON, M R, and POWELL, J H. 1992. Geological notes and local details for 1:10 000 sheet SO99NE (Willenhall and Darlaston.) 2nd Edition. Keyworth, *British Geological Survey Technical Report* WA/91/78.

HAMBLIN, R J O, and POWELL, J H. 1992. Geological notes and local details for 1:10 000 sheet SO99NW (Wolverhampton). 2nd Edition. Keyworth, *British Geological Survey Technical Report* WA/91/77.

HAYNES, J E, WOOD, G M, LAWRENCE, G, and BOURQUE, H H. 1981. Remote sensing and waste management. *Proceedings of the 7th Canadian Symposium on Remote Sensing*, 316-322.

HEAD, K H. 1994. *Manual of soils laboratory testing* , Vol. 2, Permeability, shear strength, and compressibility tests. 2nd edition. (London:Pentech Press.)

HEM, J D. 1989. Study and interpretation of the chemical characteristics of natural water, third edition, *USGS Water-Supply* Paper 2254. (United States Government Printing Office.)

HENSHAW, D L, ESTOUGH, J P and RICHARDSON, R B. 1990. Radon as a causative factor in induction of myeloid leukaemia and other cancers. *Lancet*, Vol. 335, 1008-12.

HOBBS, P R N. 1994. Falling head permeability tests on till from Wolverhampton. *British Geological Survey, Engineering Geology and Geophysics Group*, Laboratory Report 94/08.

HOOKER, P J and BANNON, M P. 1993. Methane: its occurence and hazards in construction. *CIRIA Report 130.*

JONES, H K. 1991. The investigation of vegetation change using remote sensing to detect and monitor migration of landfill gas. *Unpublished PhD thesis.* University of Aston.

KAGEY, B T and WIXON, B G. 1983. Health implications of coal developments. *in* Thornton, I. *Applied environmental geochemistry*, p.463-480 (Imperial College, London.)

KEMP, S J, and MITCHELL, C J. 1994. The clay mineralogy and particle-size distribution of a glacial till sheet from Wolverhampton. *British Geological Survey Technical Report* WG/94/23.

KNIPE, C V, LLOYD, J W, LERNER, D N, and GRESWELL, R. 1993. Rising groundwater levels in Birmingham and the engineering implications. *CIRIA Special Publication* 92, (London, CIRIA.)

LERNER, D N, GOSK, E, BOURG, A C M, BISHOP, P K, BURSTON, M W, MOUVET, C, DEGRANGES, P, and JAKOBSEN, R. 1993. Postscript: summary of the Coventry groundwater investigation and implications for the future. *Journal of Hydrology,* Vol. 149, 257-272.

LITTLE and MARTIN. 1972. A survey of zinc, lead and cadmium in soils and natural vegetation around a smelting complex. *Environmental Pollution,* Vol.3, 241-254.

McGRATH, S P and LOVELAND, P J. 1992. *The soil geochemical atlas of England and Wales.* (Blackie Academic and Professional.)

MORGAN, A V. 1973. The Pleistocene geology of the area north and west of Wolverhampton, Staffordshire, England. *Philosophical Transactions of the Royal Society of London,* Series B, Vol. 265, 233-297.

MORGAN, H and SIMMS, D L. 1988. The Shipham Report: an investigation into cadmium contamination and its implications for human health. *The Science of the Total Environment Special Issue* 75(1), 1-43.

MURPHY, B L and TOOLE, A P. 1989. Health risk assessment for arsenic contaminated soil. *Environmental Geochemistry and Health,* Vol.11(34) 163-170.

O'RIORDAN, M C, JAMES, A C, GREEN,B M R and WRIXON, A D. 1987. Exposure to radon daughters in dwellings. NRPB-G56. *National Radiological Protection Board.*(HMSO, London.)

PARLIAMENTARY OFFICE of SCIENCE and TECHNOLOGY. 1993. *Contaminated land.*

POWELL, JH. 1991. Geology of the Penn district. *British Geological Survey Technical Report.* W/91/76.

POWELL, JH, GLOVER, BW, and WATERS, CN. 1992. A geological background for planning and development in the 'Black Country'. *British Geological Survey Technical Report* WA/92/33.

RAMONDETTA, P J and HARRIS, W H. 1978. Heavy metals distribution in Jamaica Bay sediments. *Environmental Geology,* Vol.2,45-148.

RIVETT, M O, LERNER, D N, LLOYD, J W, and CLARK, L . 1990. Organic contamination in the Birmingham aquifer, U.K. *Journal of Hydrology,* Vol. 113, 307-323.

ROYAL COMMISSION on ENVIRONMENTAL POLLUTION. 1983. *Lead in the environment.*(London, HMSO.)

SIMSIMAN, G V, CHESTERS, G, and ANDREN, A W. 1987. Effect of ash disposal ponds on groundwater quality at a coal-fired power plant. *Water Resources,* 21/4, 417-426.

THORNTON,I, Culbard,E B, MOORCROFT,S, WATT,J, WHEATLEY, M, THOMPSON, M and THOMAS, J F A. 1985. Metals in urban dusts and soils. *Environmental Technology Letters,*Vol 6, 137-145.

THORNTON, I. 1986. Metal contamination of soils in urban areas. *in* Soils in the urban environment (editors Bullock, P and Gregory, P J).

THORNTON, I and Howarth, R. 1986. *Applied geochemistry in the 1980s.* Nantwich, Shiva (Shiva geology series)

THORNTON, I. 1983. Applied environmental geochemisty. (I Thornton, editor) (London Academic Press.)

WEALTHALL, G P, WARD, R S, LEADER, R U, and TRICK, J K. 1995. East Park, Wolverhampton: an environmental site investigation. *British Geological Survey Technical Report,* WE/95/17R.

WEBB, J S, THORNTON, I, THOMPSON, M, HOWARTH, R J and LOWENSTEIN, P L. 1978. The Wolfson geochemical atlas of England and Wales.(Oxford University Press, Oxford.)

WHITEHEAD, T H, ROBERTSON, T, POCOCK, RW, and DIXON, EEL. 1928. The country between Wolverhampton and Oakengates. *Memoir of the Geological Survey of Great Britain,* Sheet 159.

YOUNGER, P L. 1993. Possible environmental impact of the closure of two collieries in County Durham. *Journal of the Institution of Water and Environmental Managers,* Vol. 7, 521-531.

Figures and Plates

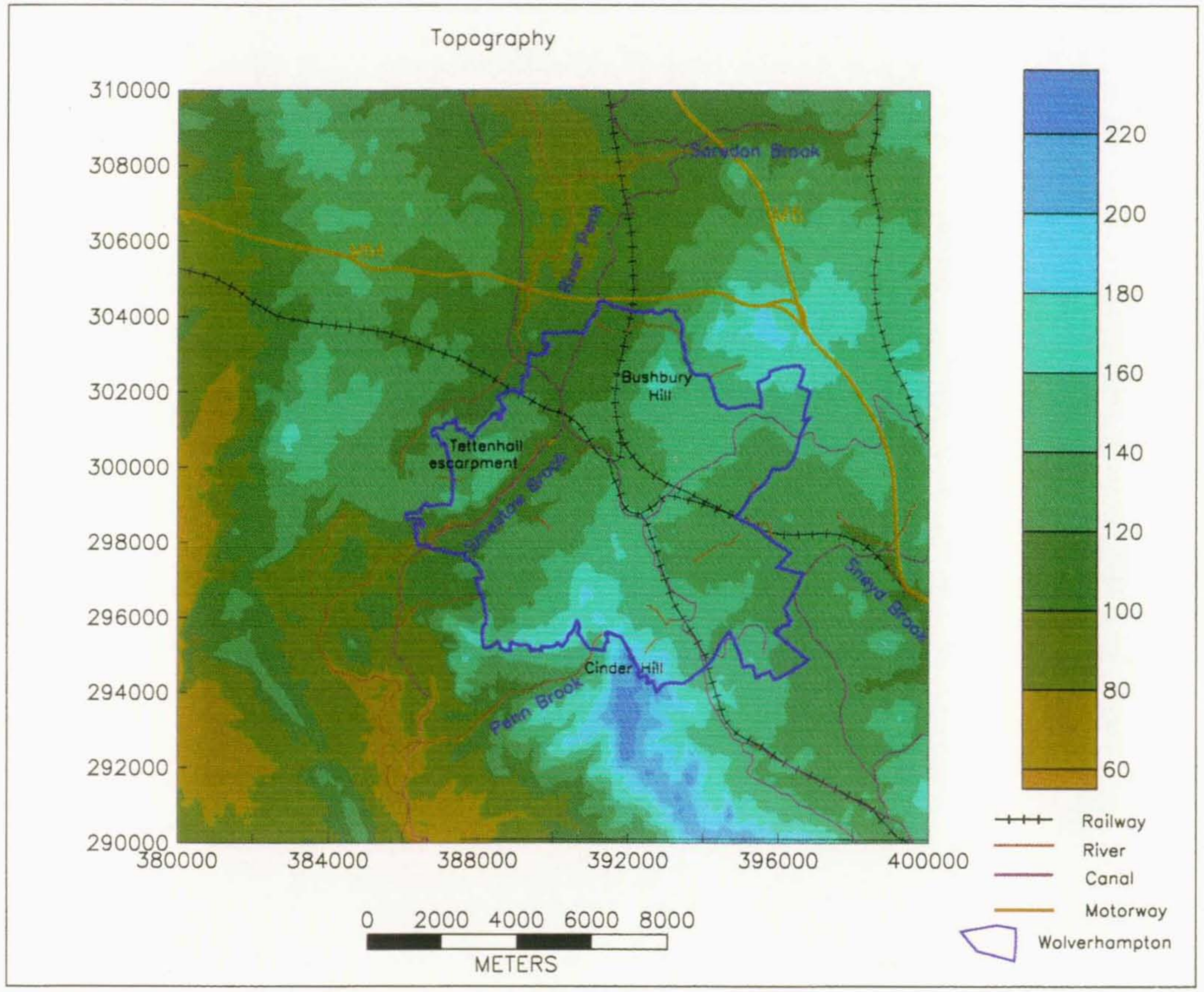


Figure 1. Regional setting

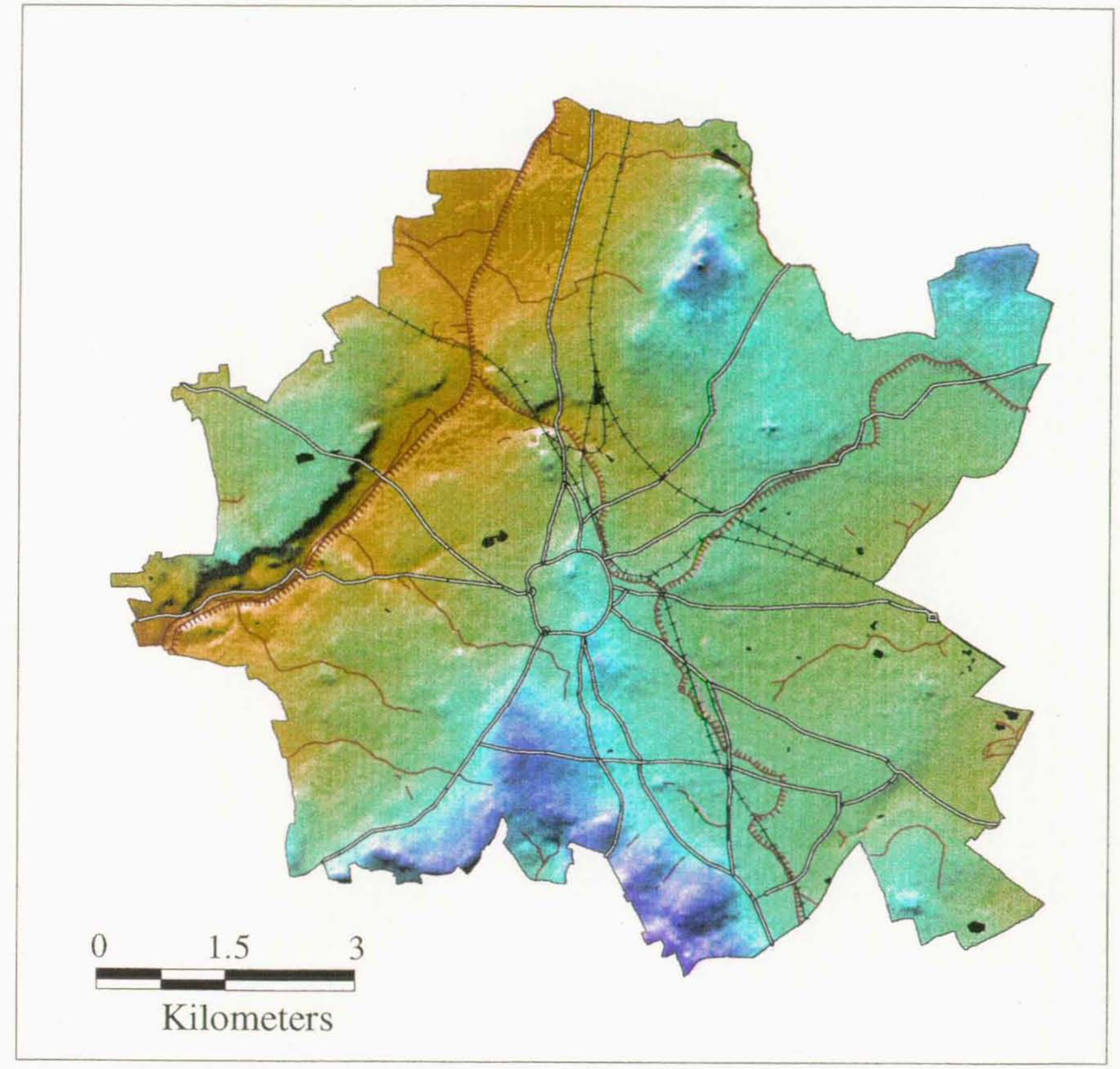


Figure 2. Wolverhampton Metropolitan Borough

[1, 2]

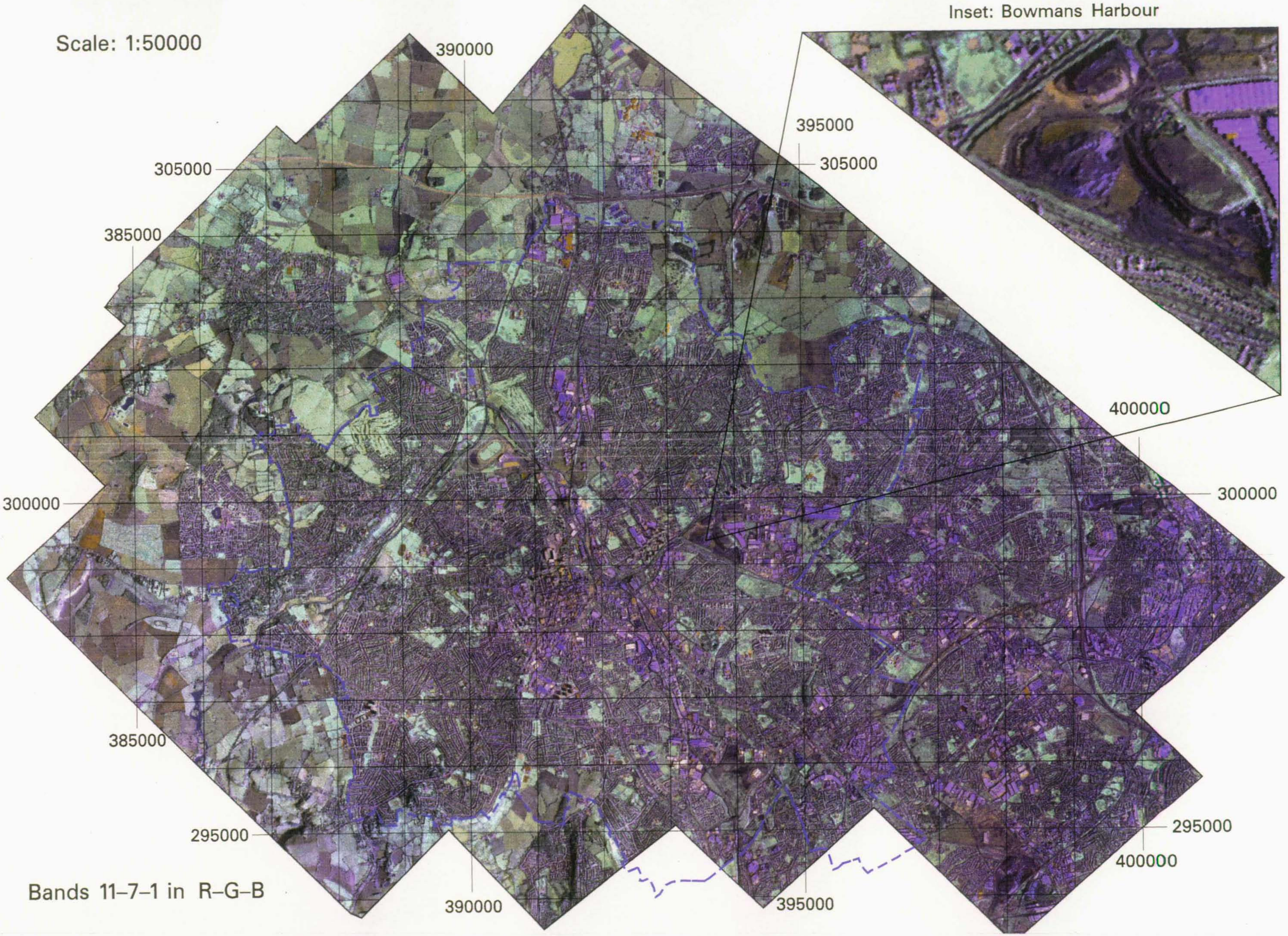
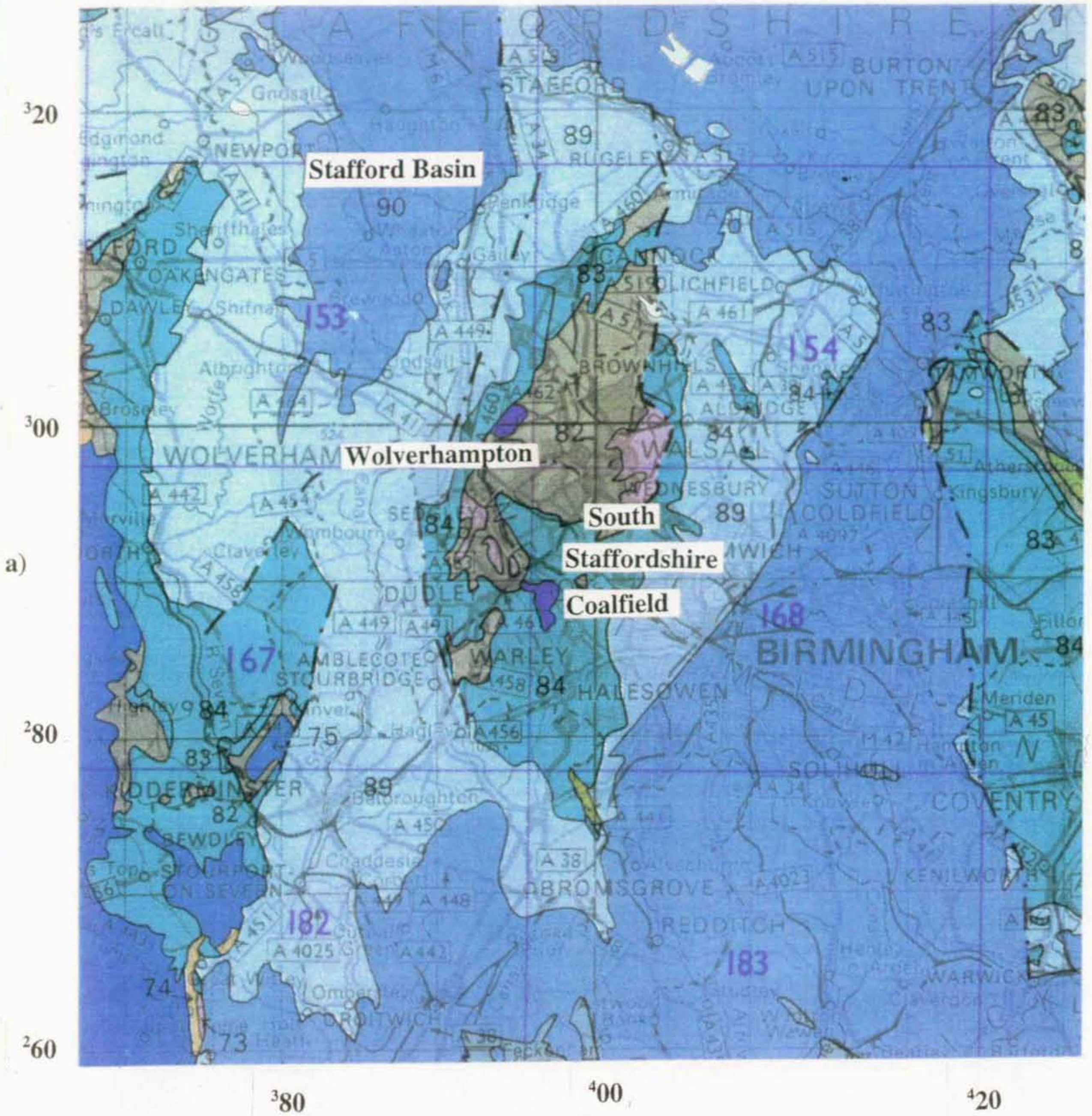


Figure 3. False colour composite image of the Wolverhampton area

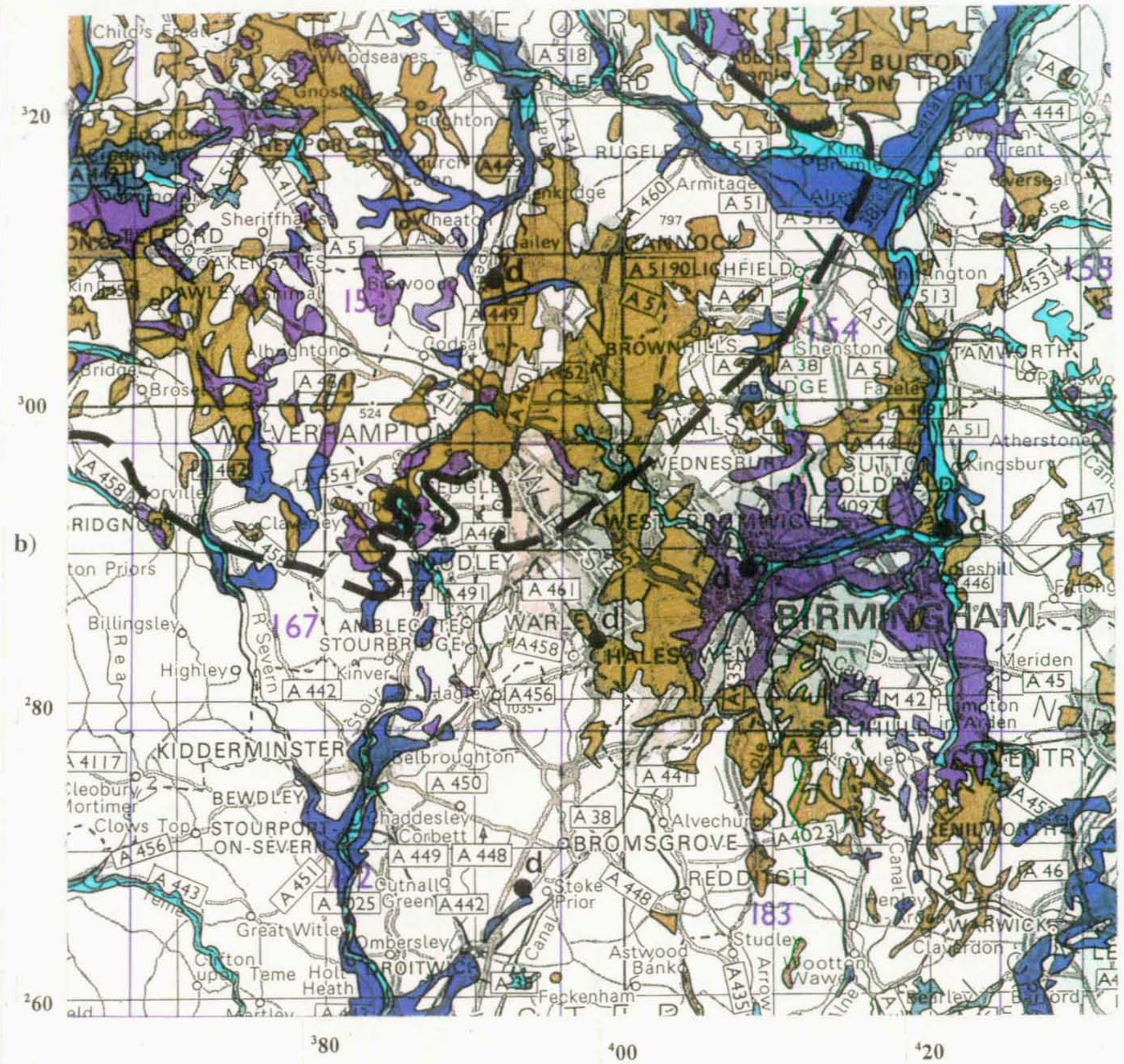
[3]

a)



- 91 Jurassic
- 90 Triassic mudstones
- 89 Permian and Triassic sandstones
- 84 Carboniferous (Westphalian):
  - 83 Barren measures (mainly red-beds)
  - 82 Productive Coal Measures
- 75 Devonian
- 74, 73, 72 Silurian
- 35 Dolerite

b)



- Peat
- Lacustrine clays, silts and sands
- Alluvium
- River Terrace Deposits (mainly sand and gravel)
- Glacial sand and gravel
- Till
- Approximate southern limit of Devensian glaciation

Figure 4. Regional geological setting of the project area

[4]

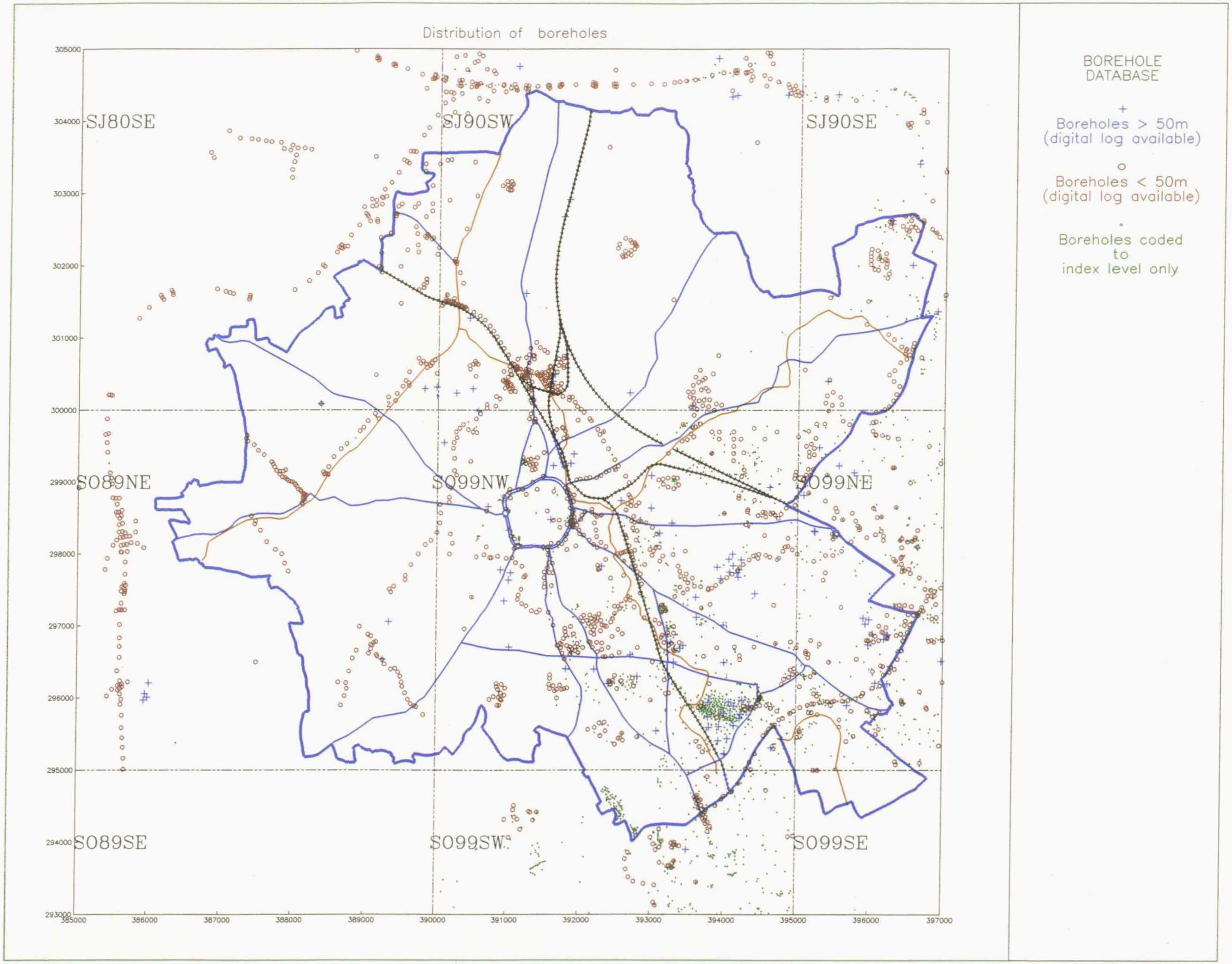


Figure 5. Distribution of boreholes used in map compilation

[5]

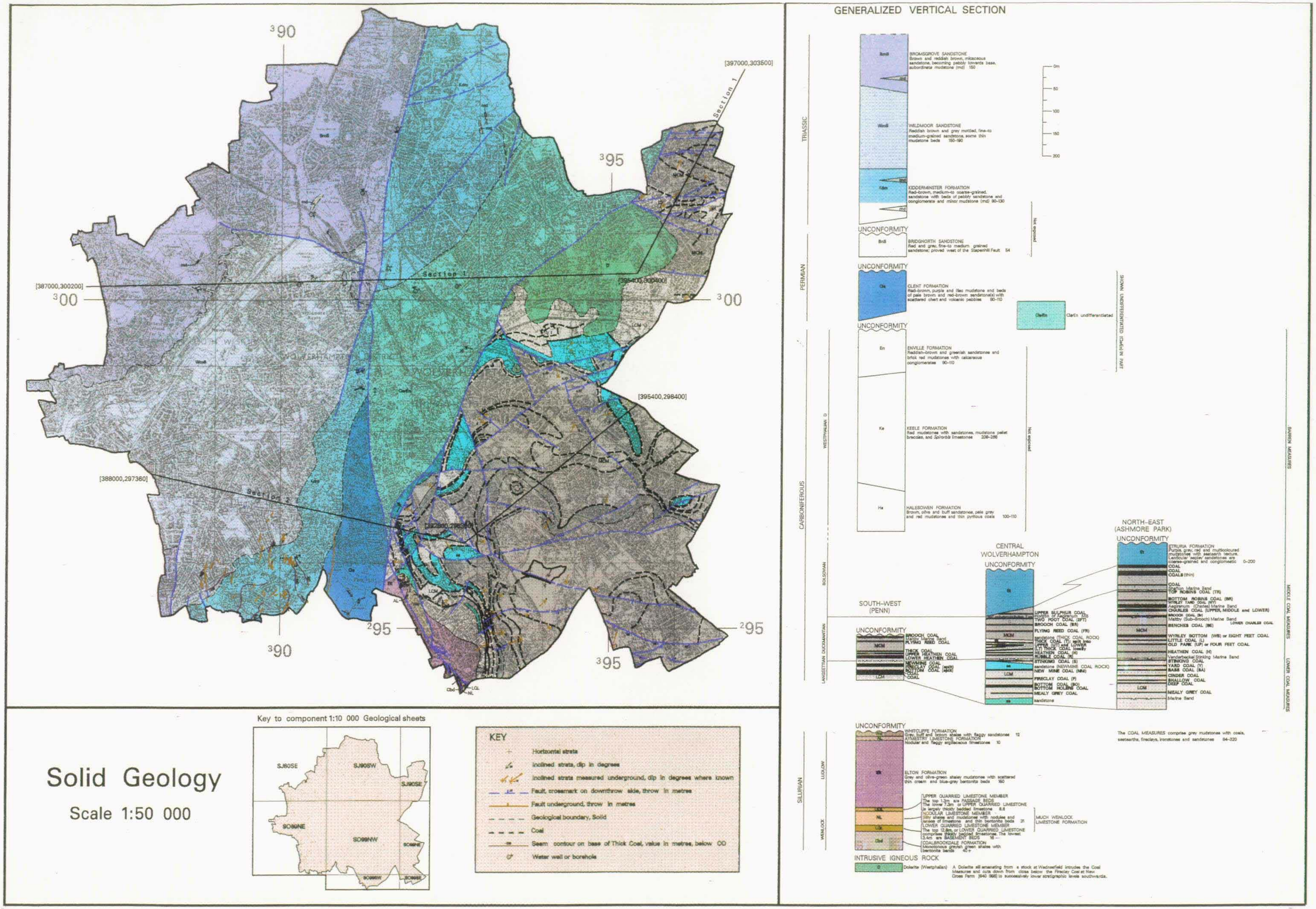


Figure 6. Solid geology of the Borough of Wolverhampton

[6]

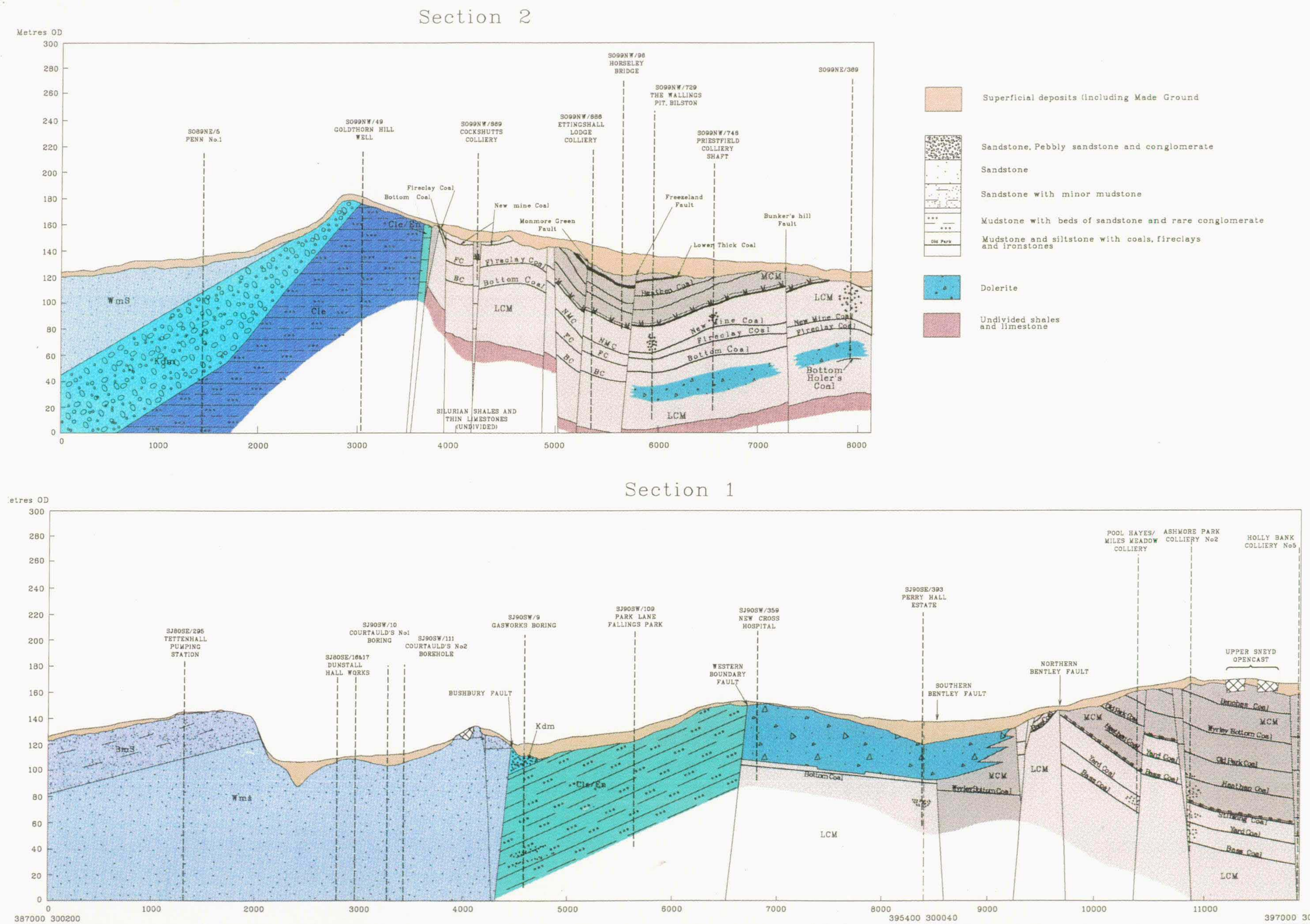


Figure 7. Cross sections showing the general relations of the rocks along the lines on Figure 6

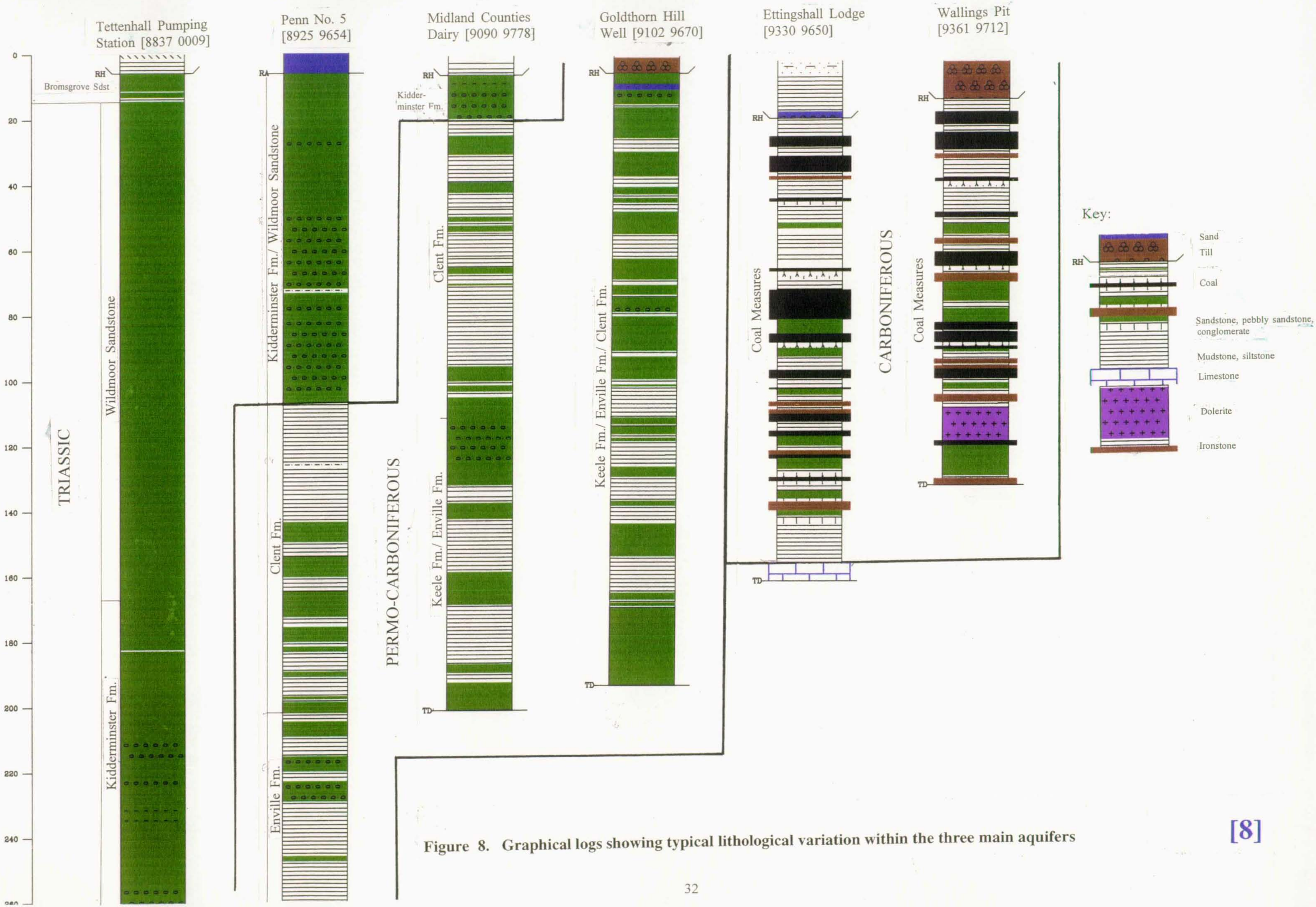


Figure 8. Graphical logs showing typical lithological variation within the three main aquifers

[8]

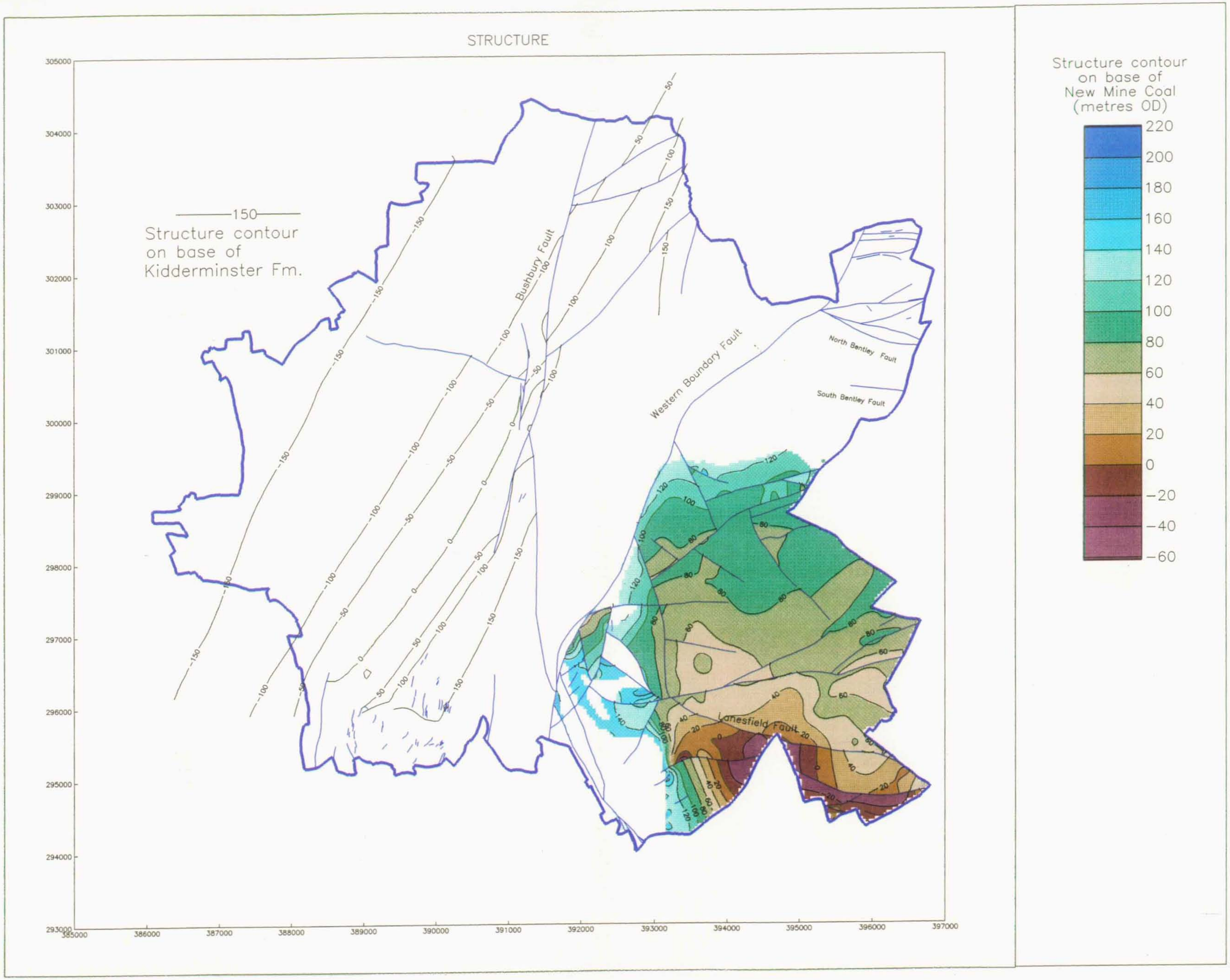


Figure 9. Structural map of the area

[9]

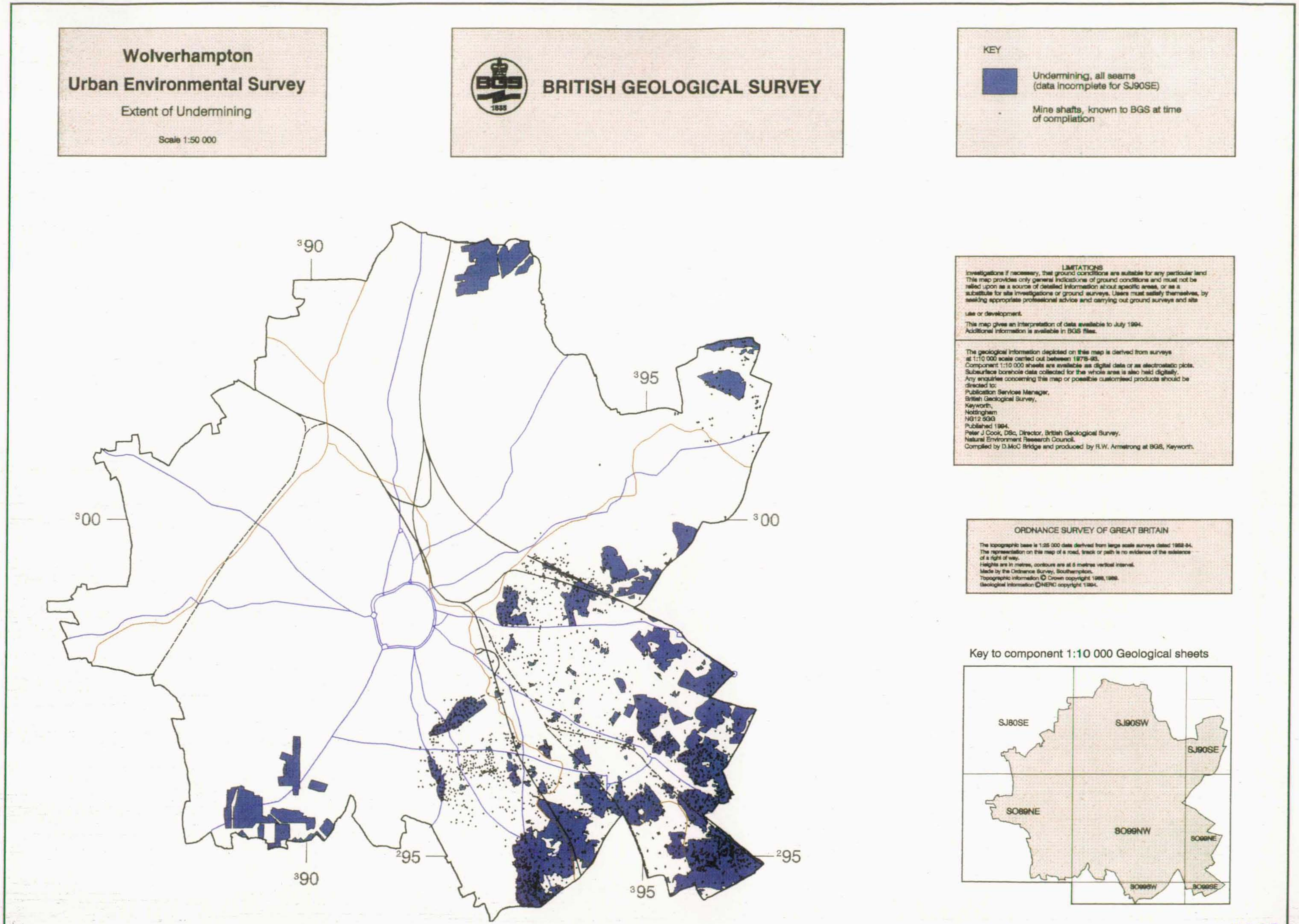


Figure 10. Extent of undermining (all seams) and shaft distribution

[10]

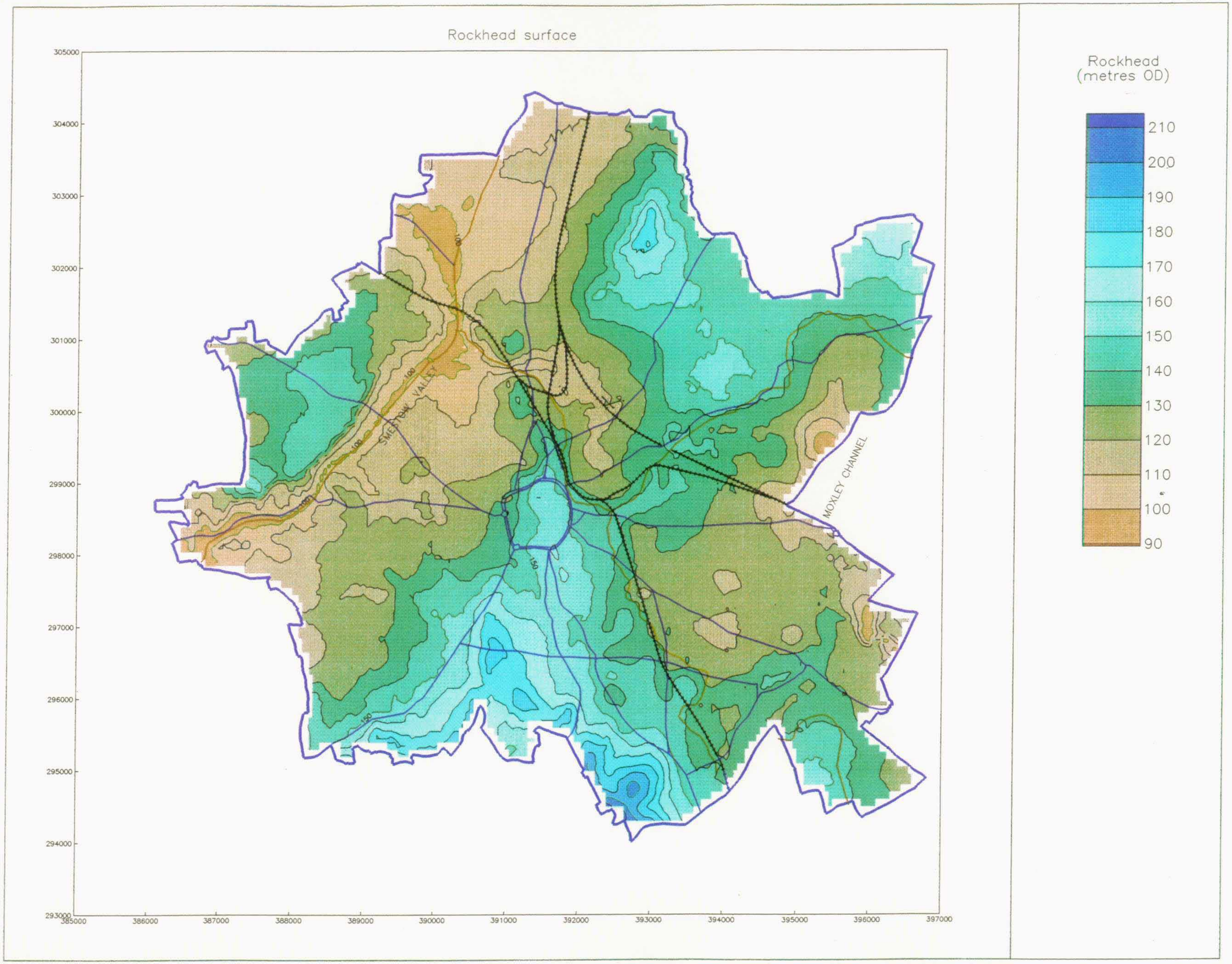


Figure 11. Rockhead contour map showing the elevation of the rockhead surface beneath drift

[11]

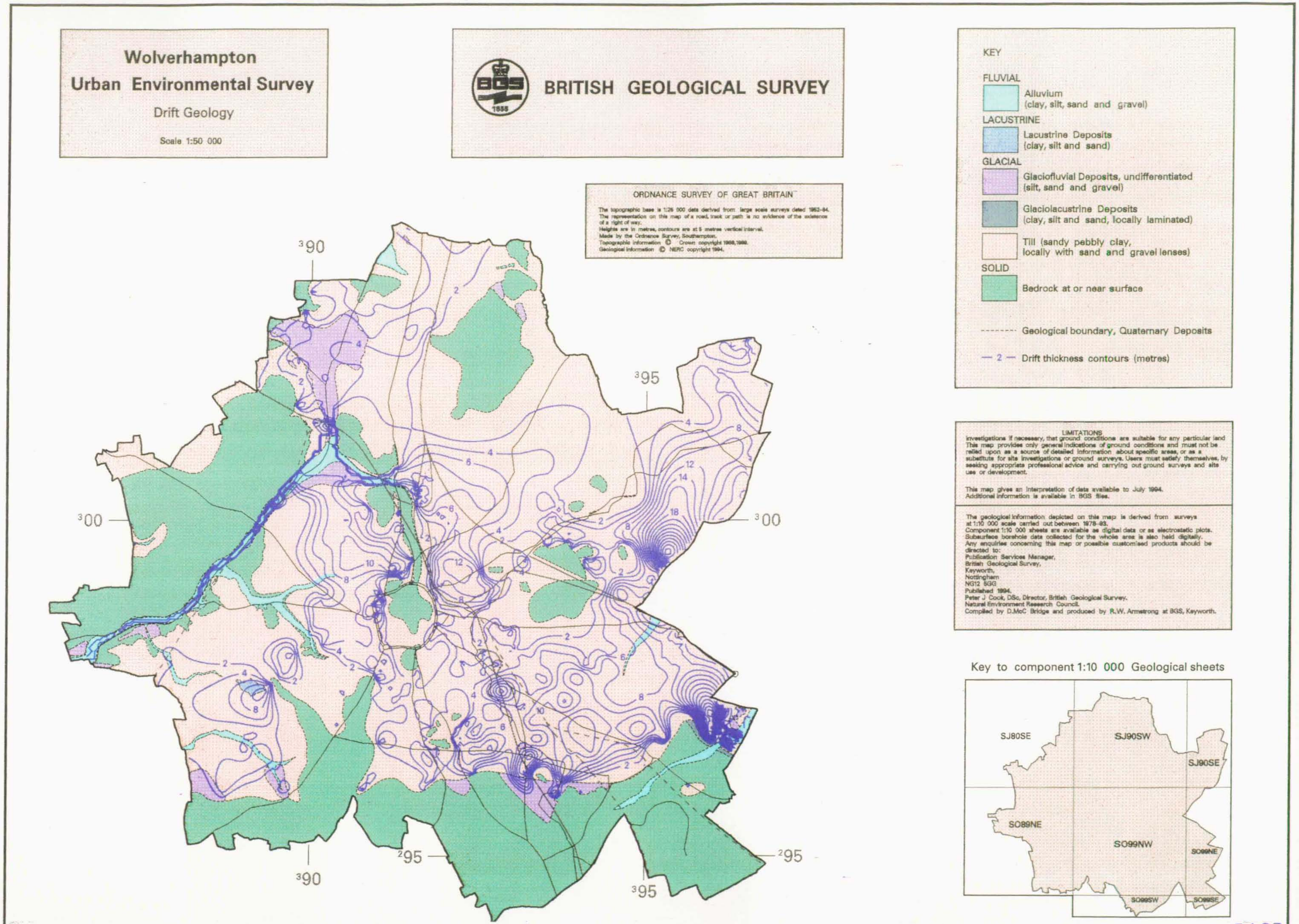


Figure 12. Distribution and thickness of the superficial (drift) deposits

[12]

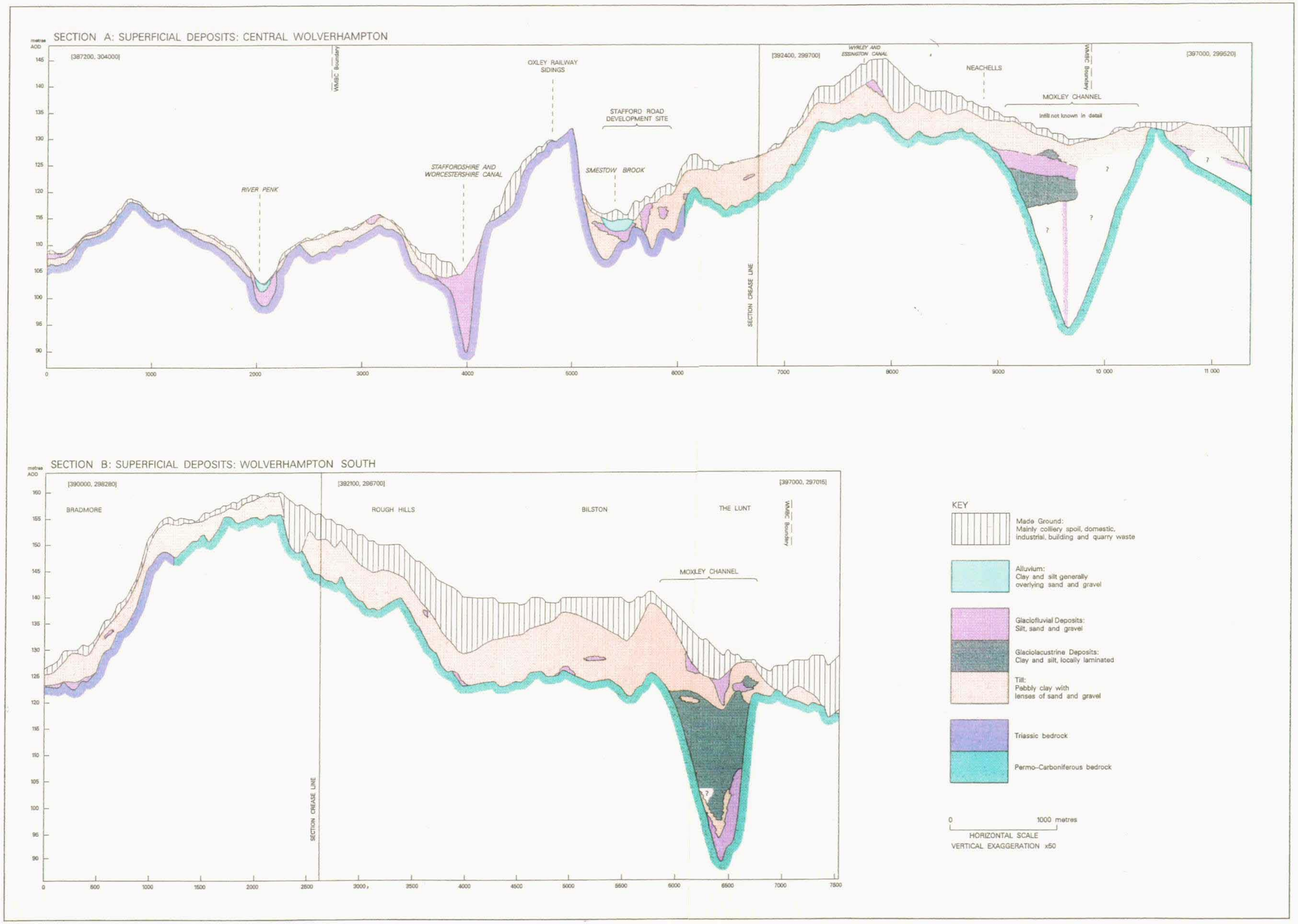


Figure 13. Cross sections (east-west) showing the relationship of the drift deposits across central and south Wolverhampton

[13]

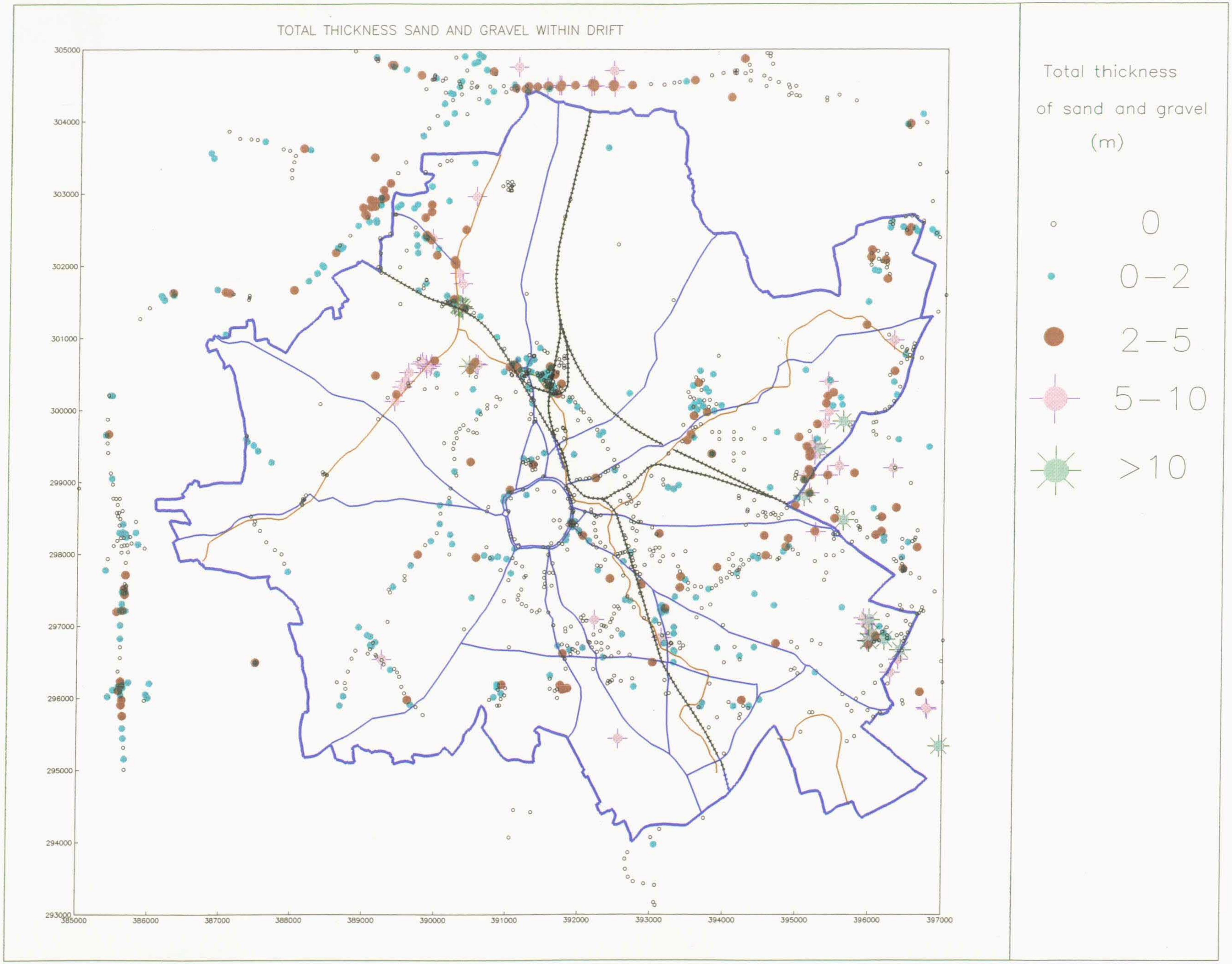


Figure 15. Thickness of sand and gravel reported in boreholes

[15]

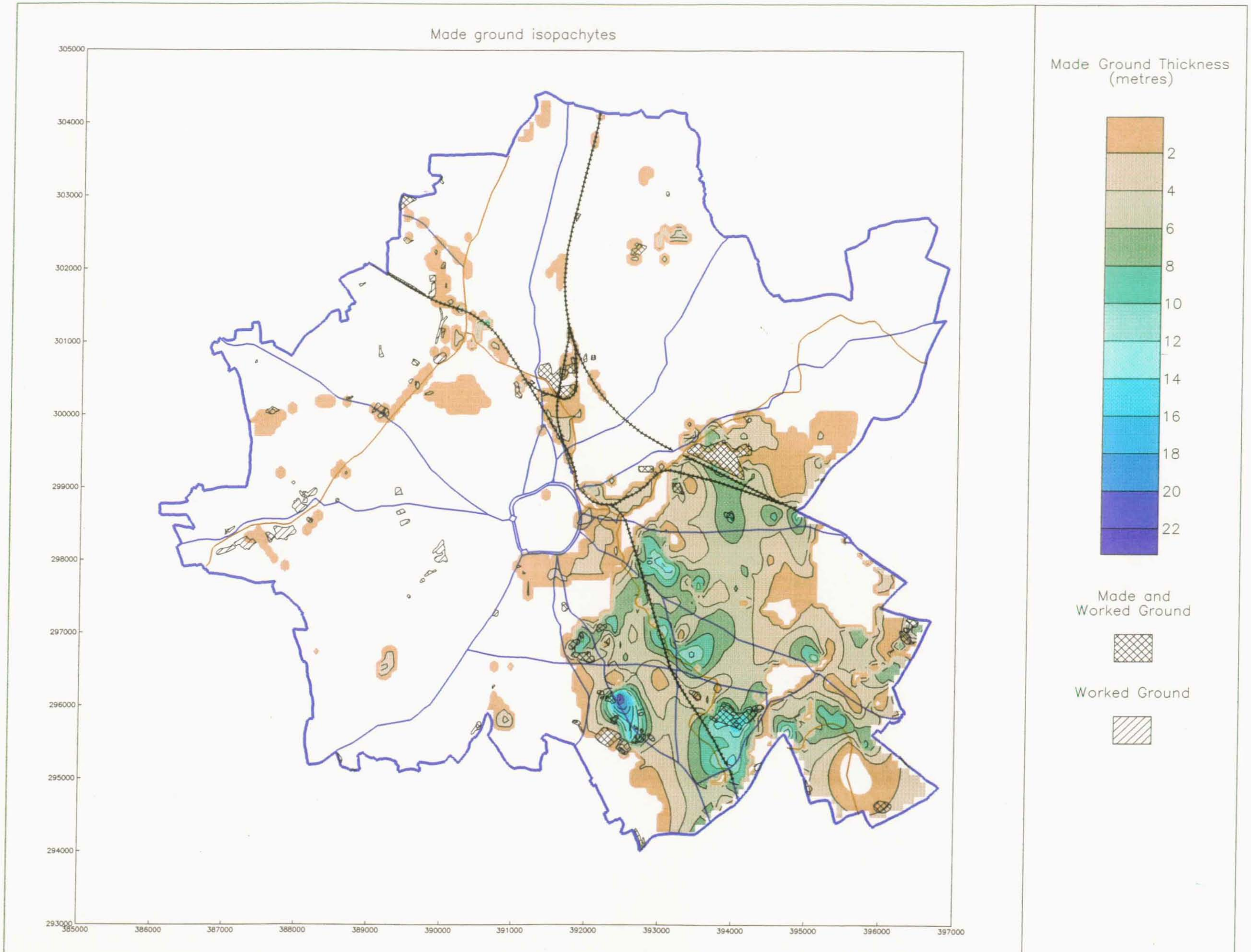


Figure 16. Map showing a) distribution and thickness of Made Ground; b) location of quarries and other open excavations (worked ground) c) infilled excavations (made and worked ground)

[16]

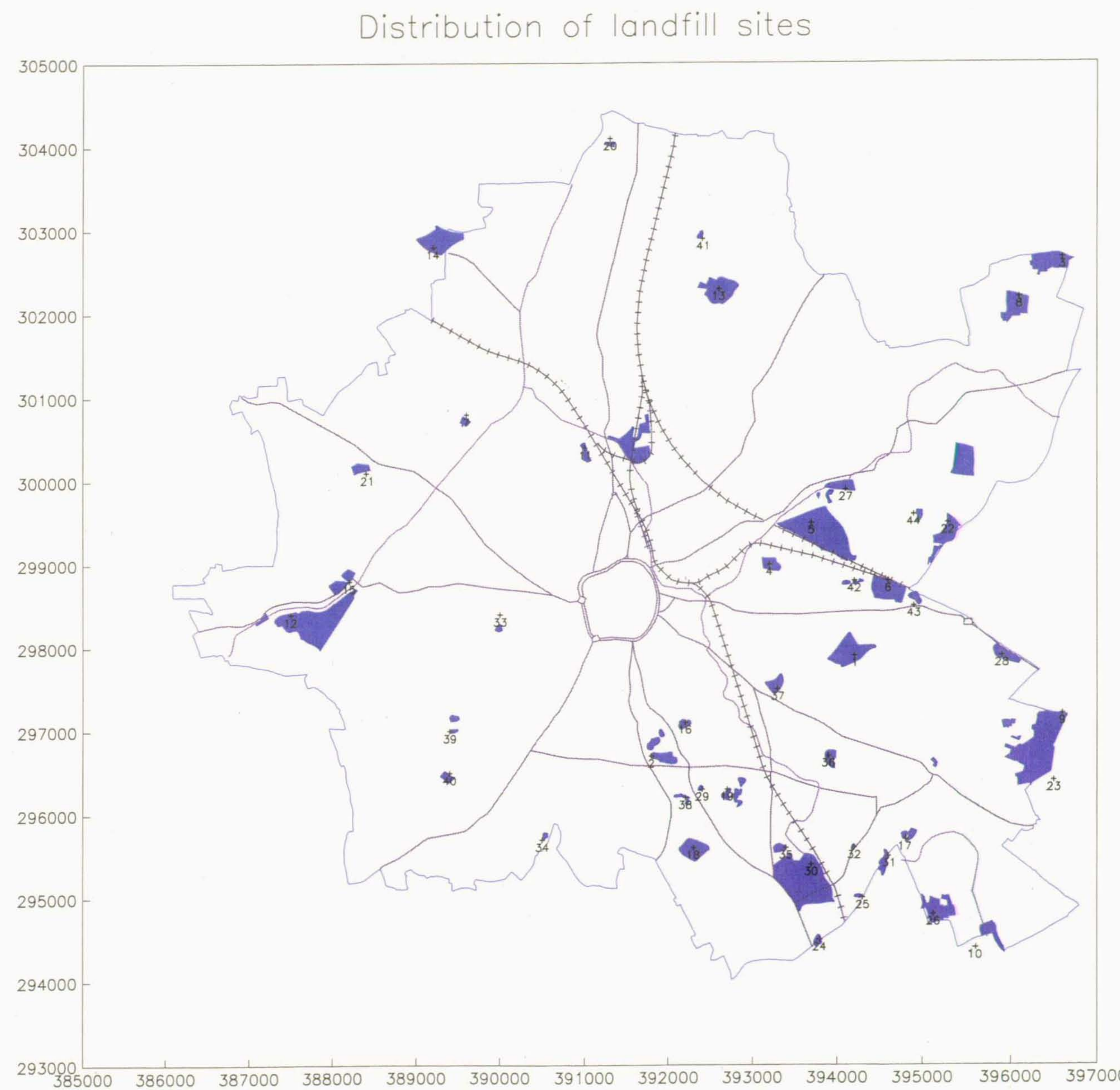


Figure 17. Landfill sites

[17]

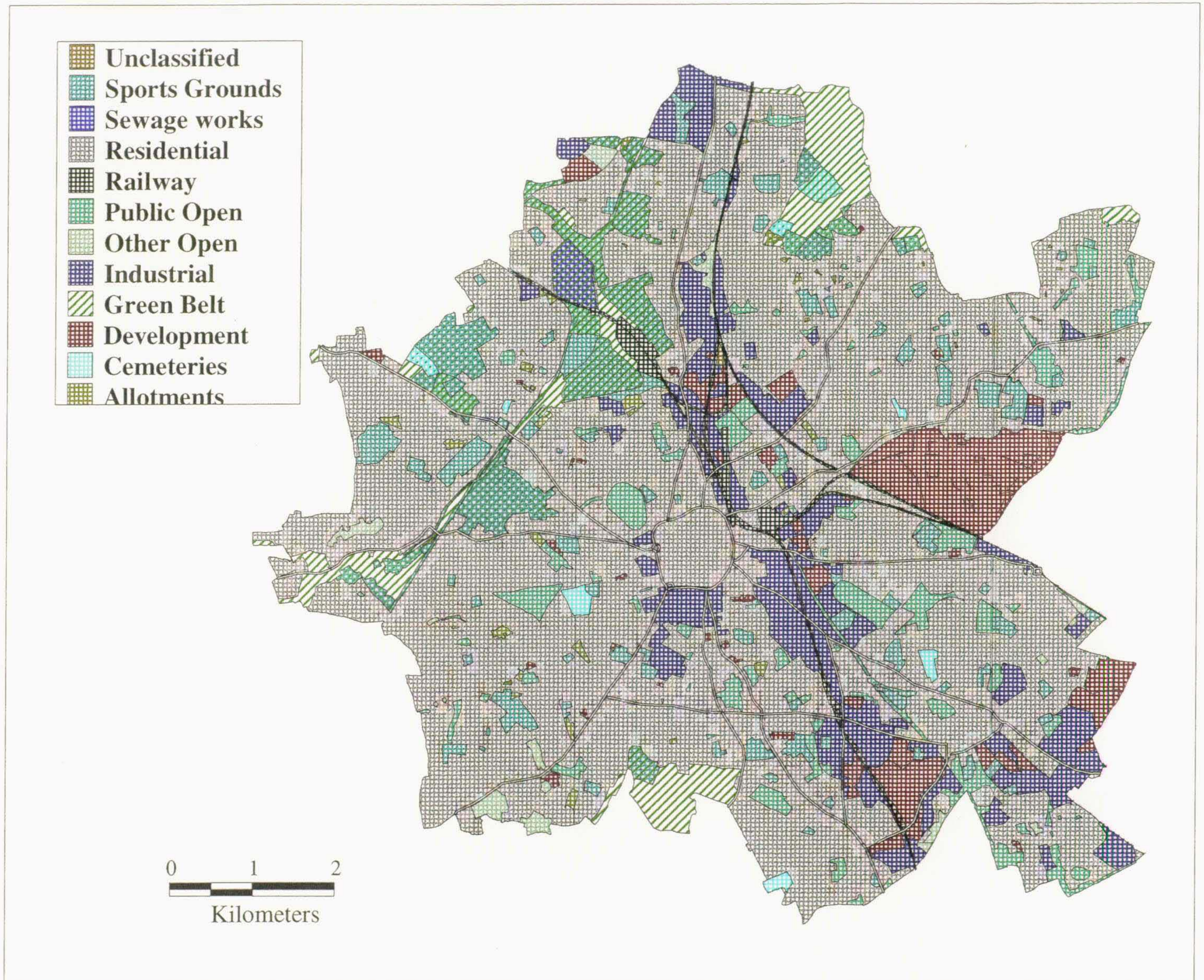


Figure 18. Land-use map (1990s) based on the Unitary Development Plan for Wolverhampton

[18]

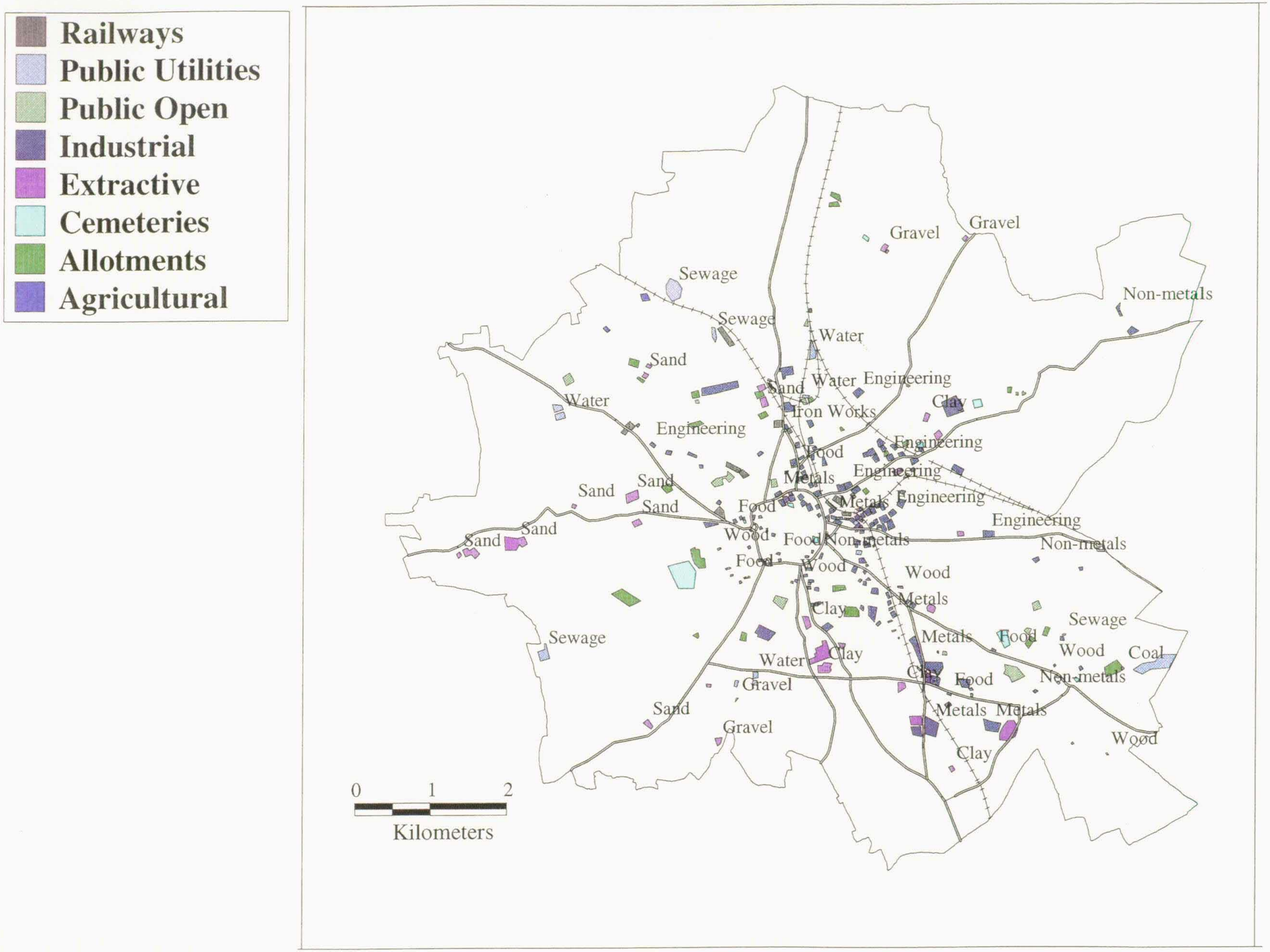


Figure 19. Land-use (1900s) compiled from early editions of Ordnance Survey maps

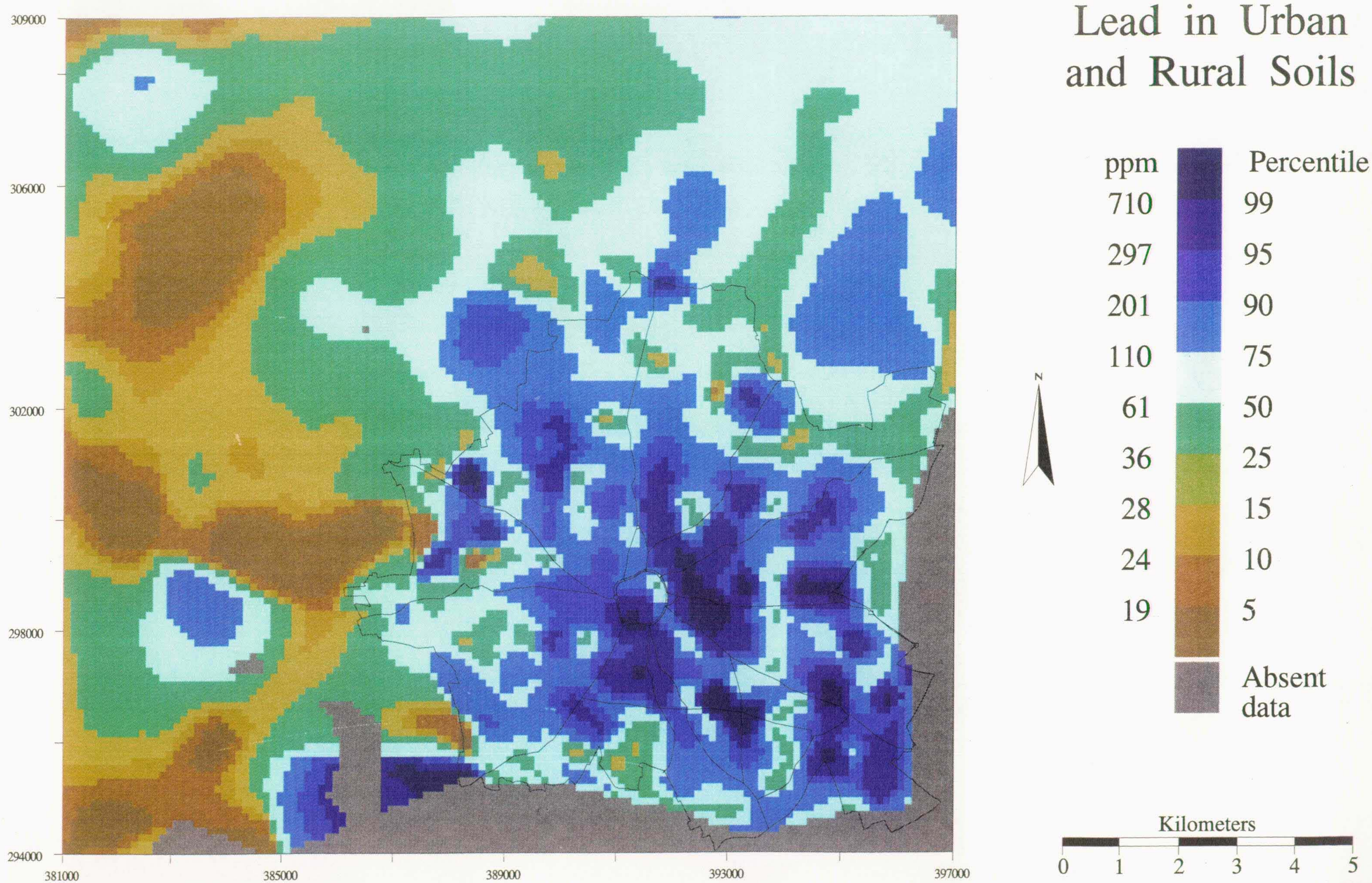


Figure 20. Lead in rural and urban soils (gridded data)

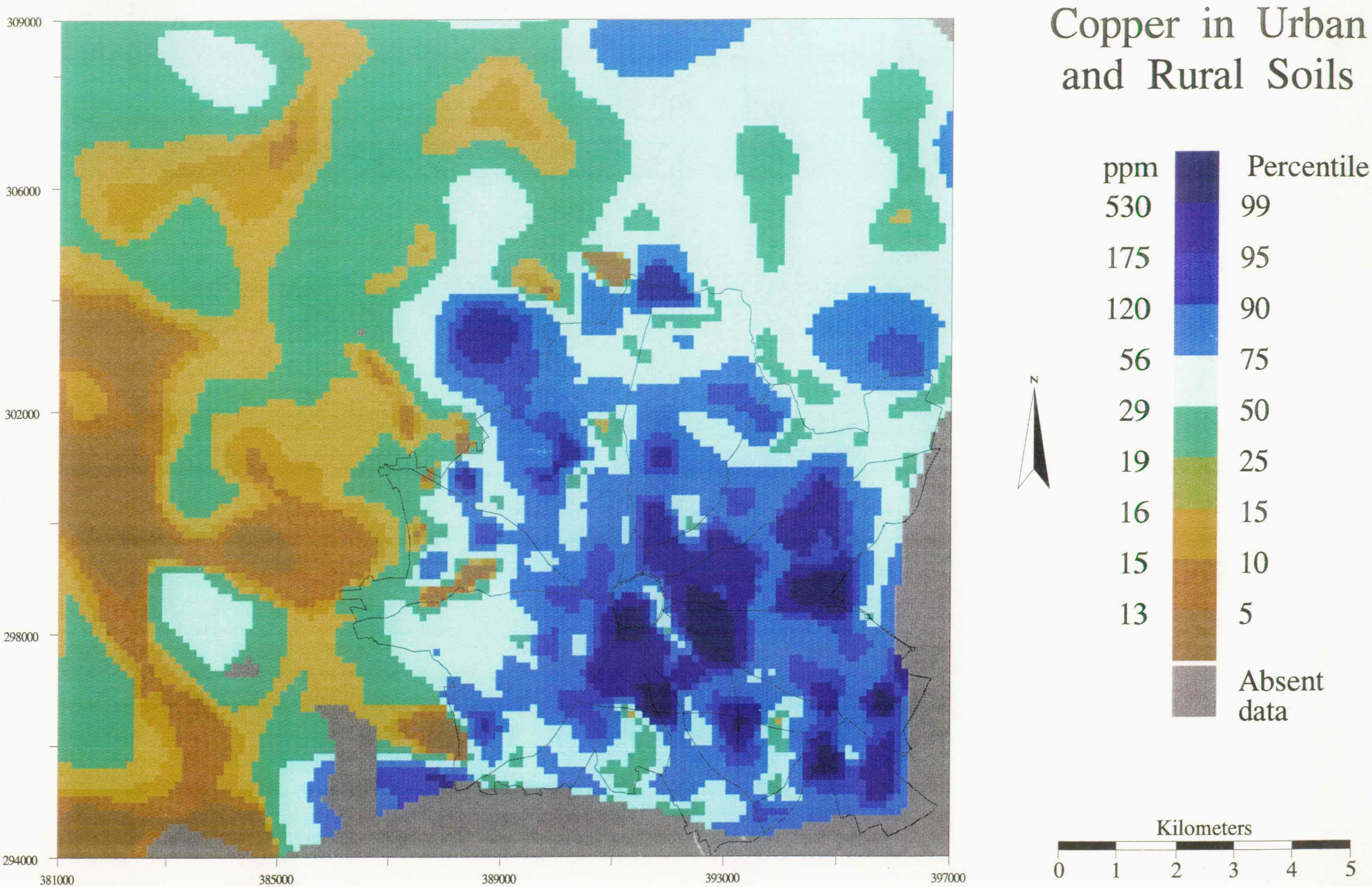


Figure 21. Copper in rural and urban soils (gridded data)

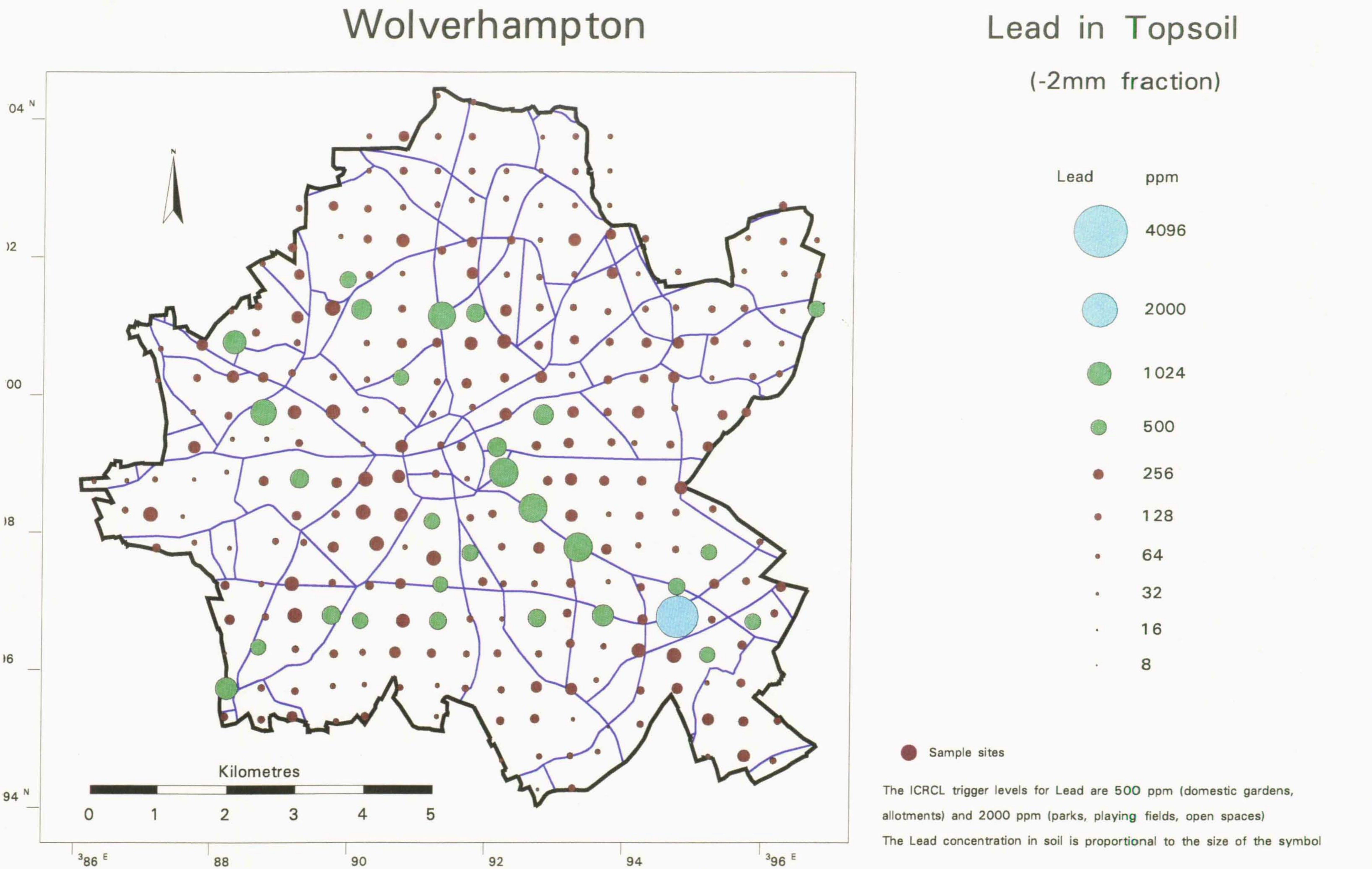
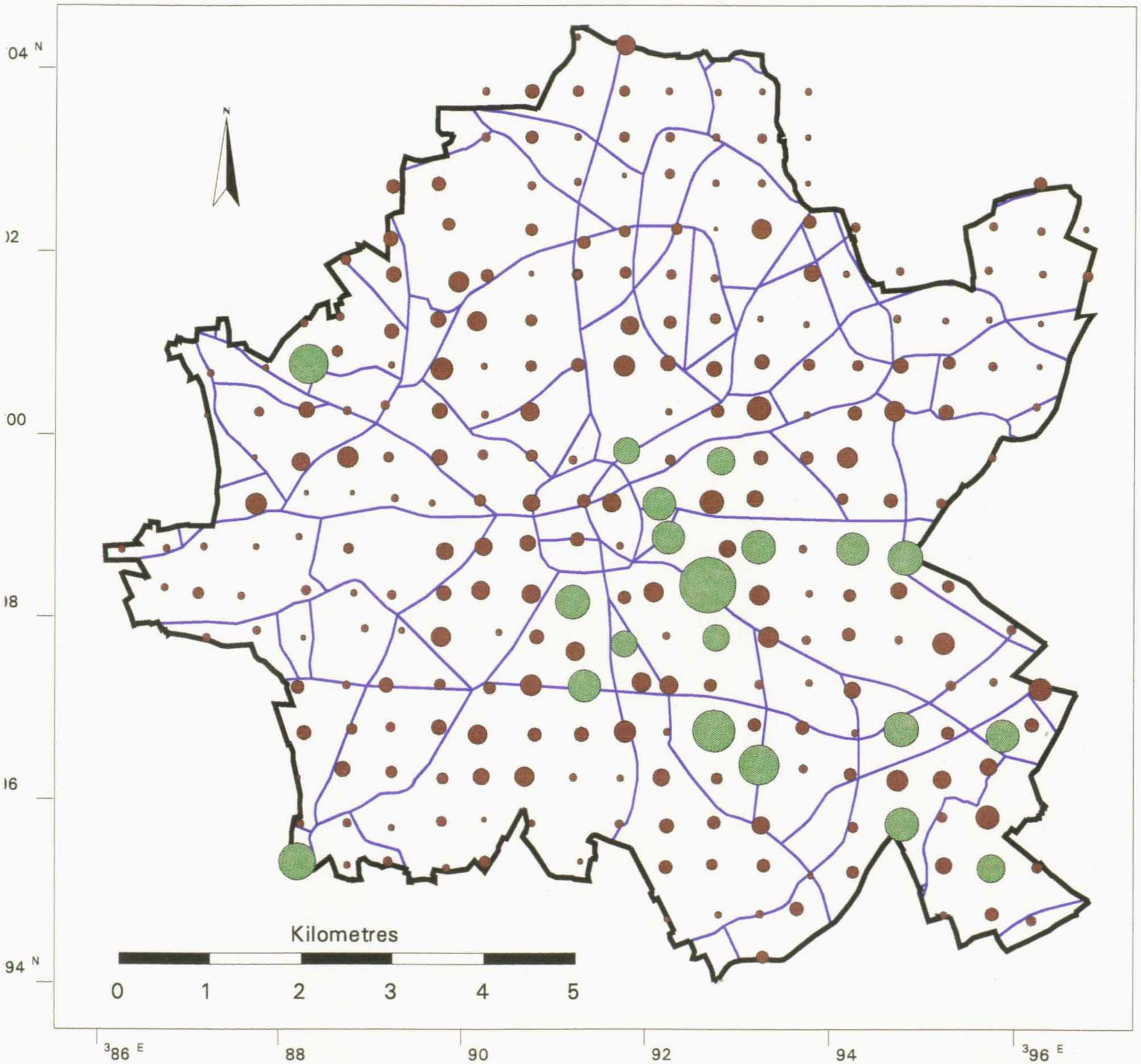


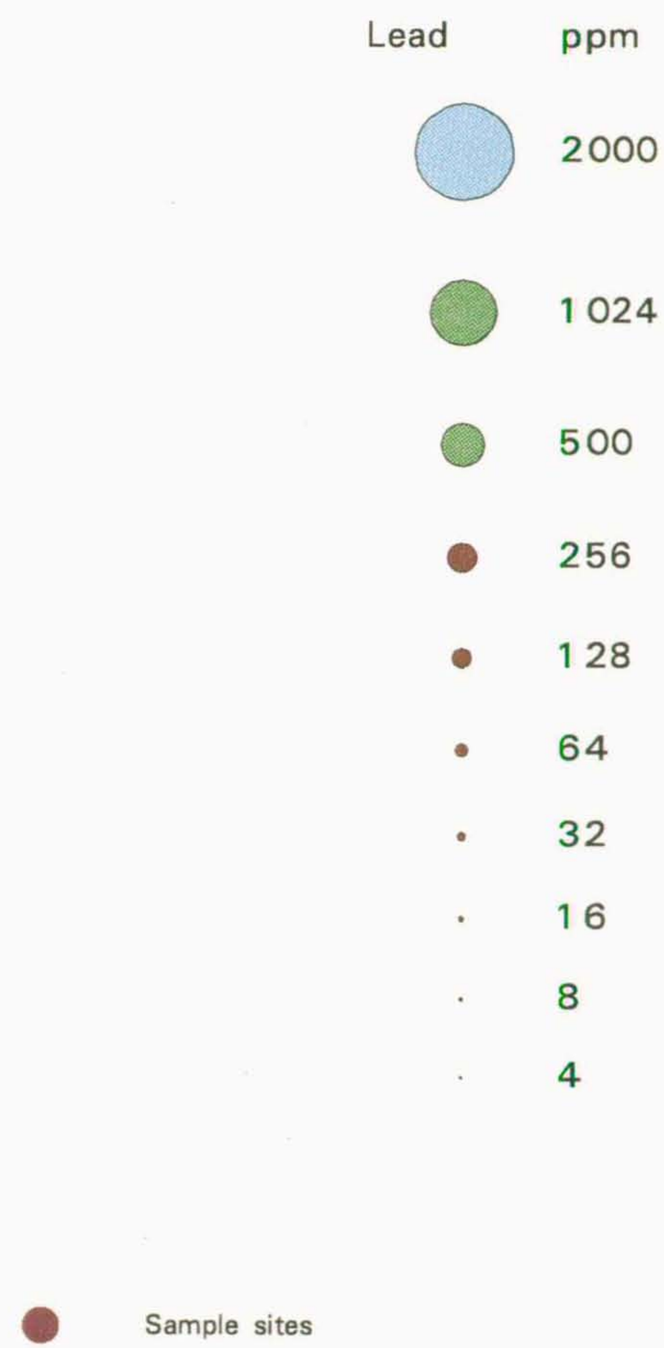
Figure 22. Lead in topsoil (point data)

Wolverhampton

Lead in Subsurface Soil

(-150μm fraction)





The ICRCL trigger levels for Lead are 500 ppm (domestic gardens, allotments) and 2000 ppm (parks, playing fields, open spaces)

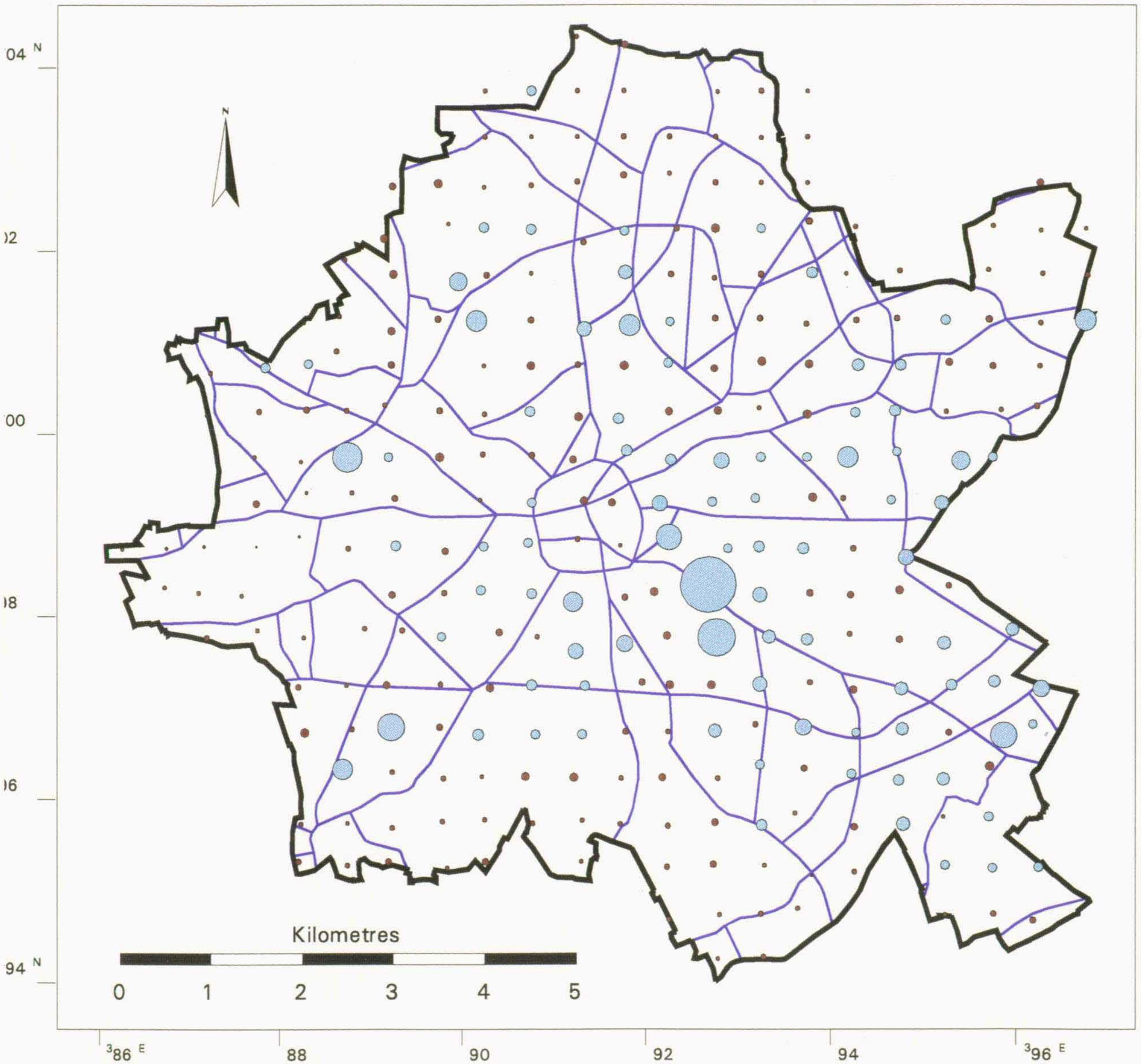
The Lead concentration in soil is proportional to the size of the symbol

Figure 23. Lead in subsurface soil

Wolverhampton

Copper in Topsoil

(-2mm fraction)



Copper ppm

4096

2048

1024

512

256

130

64

32

16

8

Sample sites

The ICRCL trigger level for Copper is 130 ppm (anywhere plants are to be grown).

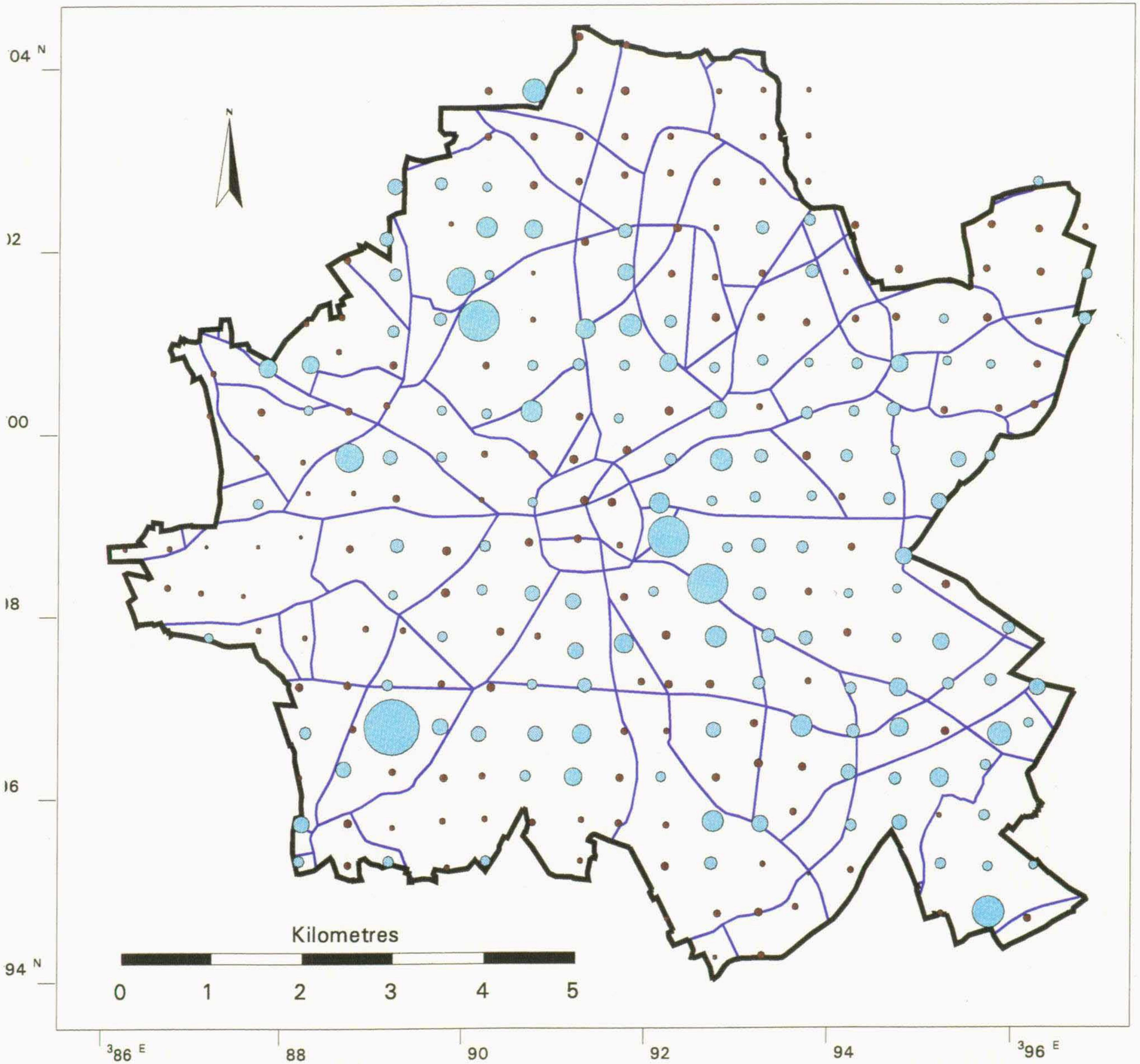
The Copper concentration in soil is proportional to the size of the symbol

Figure 24. Copper in topsoil

Wolverhampton

Zinc in Topsoil

(-2mm fraction)



Zinc ppm

8192

4096

2048

1024

512

300

128

64

32

16

Sample sites

The ICRCL trigger level for Zinc is 300 ppm

(anywhere plants are to be grown).

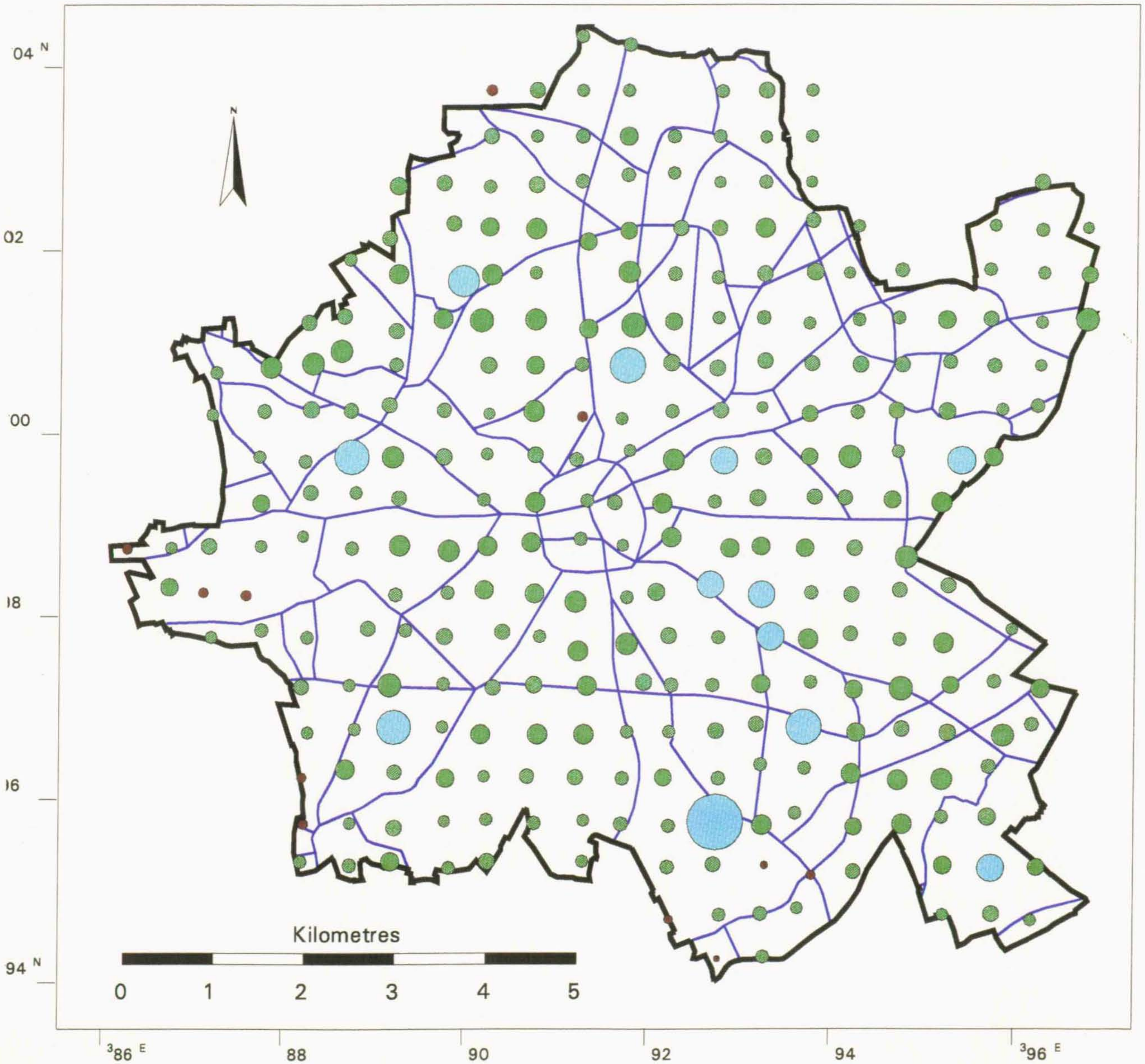
The Zinc concentration in soil is proportional to the size of the symbol

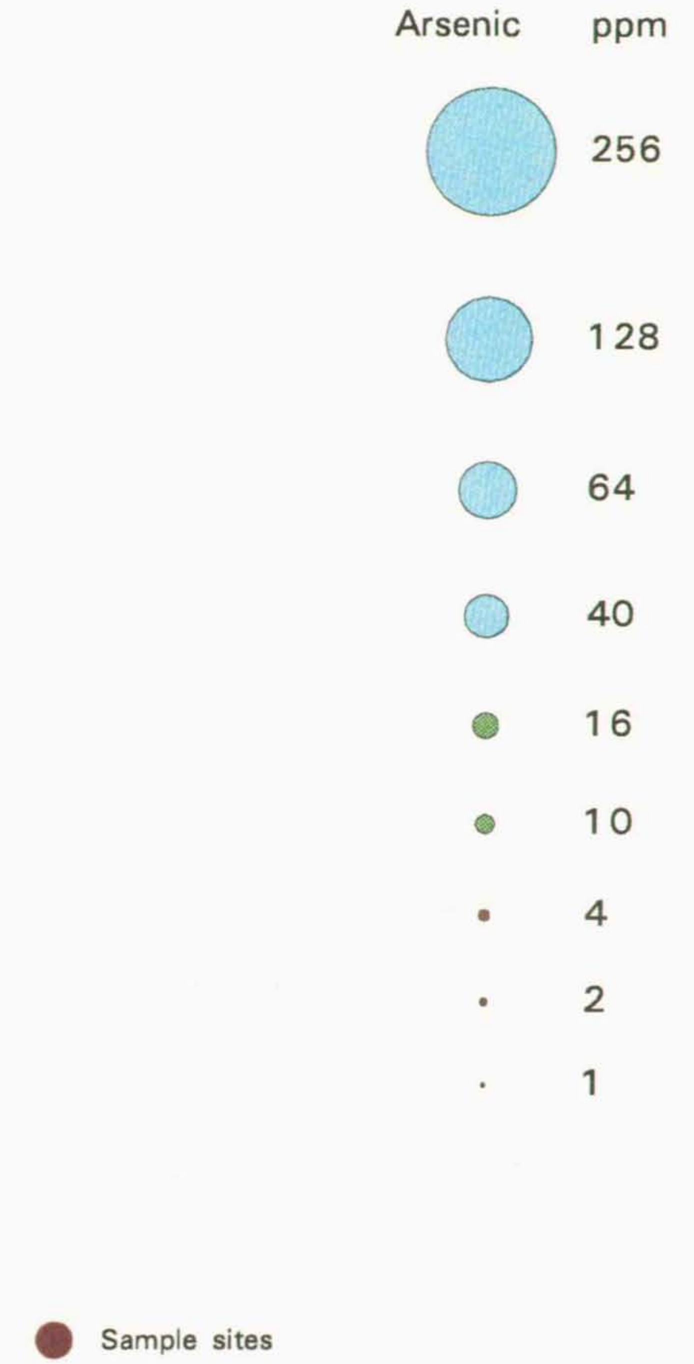
Figure 25. Zinc in topsoil

Wolverhampton

Arsenic in Topsoil

(-2mm fraction)





The ICRCL trigger levels for Arsenic are 10 ppm (domestic gardens, allotments) and 40 ppm (parks, playing fields, open spaces)

The Arsenic concentration in soil is proportional to the size of the symbol

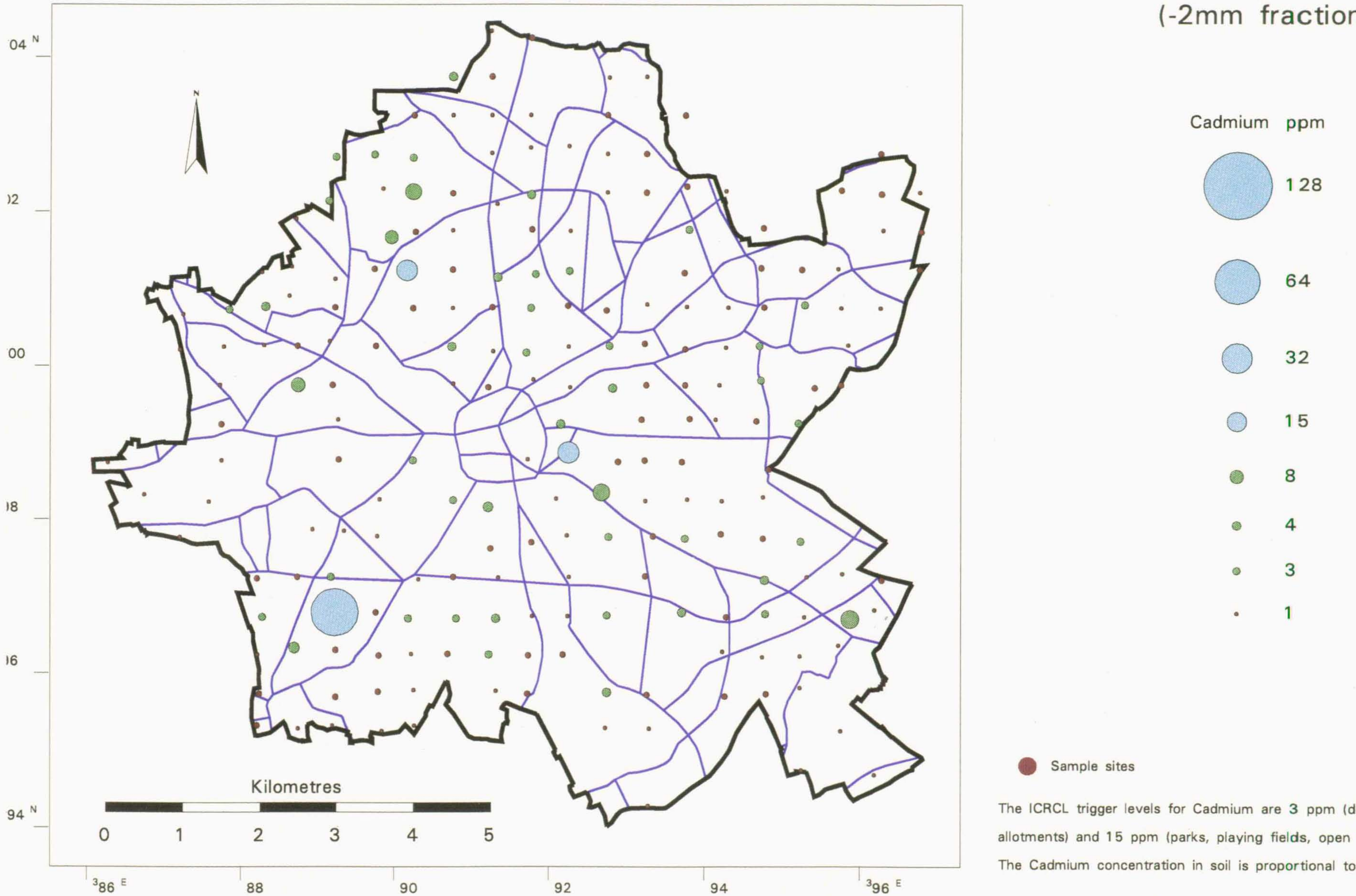
Figure 26. Arsenic in topsoil

[26]

Wolverhampton

Cadmium in Topsoil

(-2mm fraction)



The ICRCL trigger levels for Cadmium are 3 ppm (domestic gardens, allotments) and 15 ppm (parks, playing fields, open spaces)

The Cadmium concentration in soil is proportional to the size of the symbol

Figure 27. Cadmium in topsoil

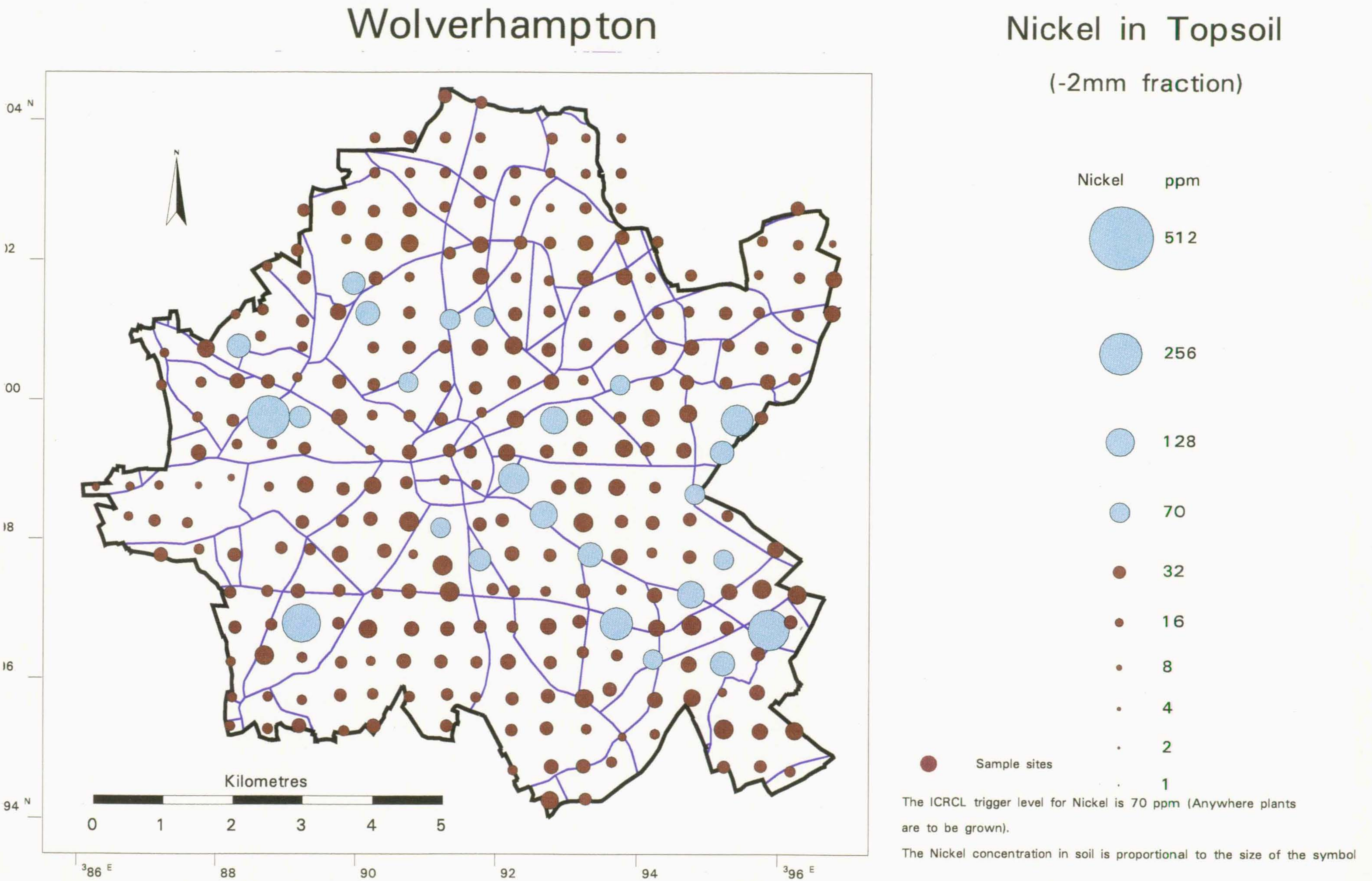


Figure 28. Nickle in topsoil

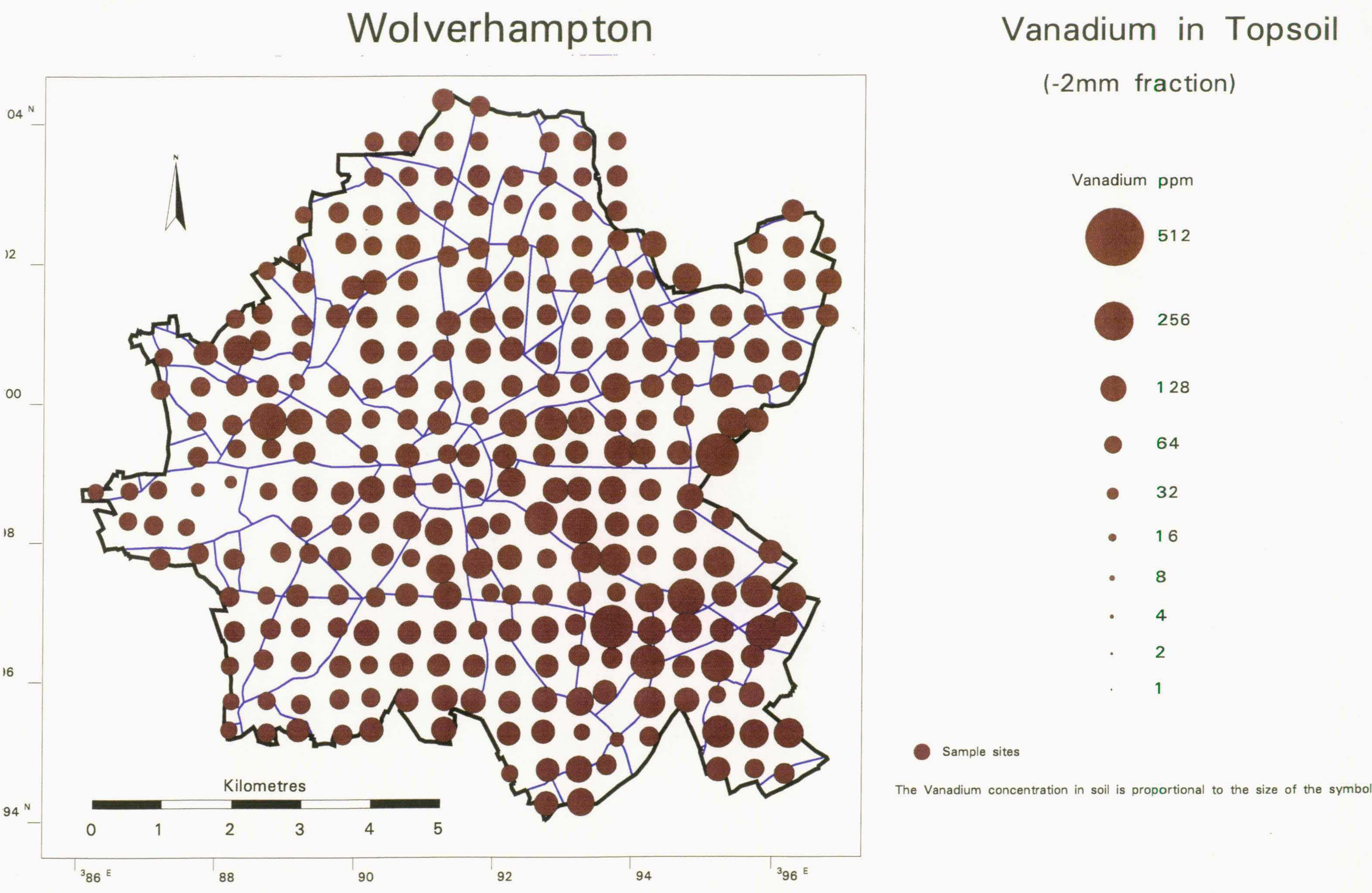


Figure 29. Vanadium in topsoil

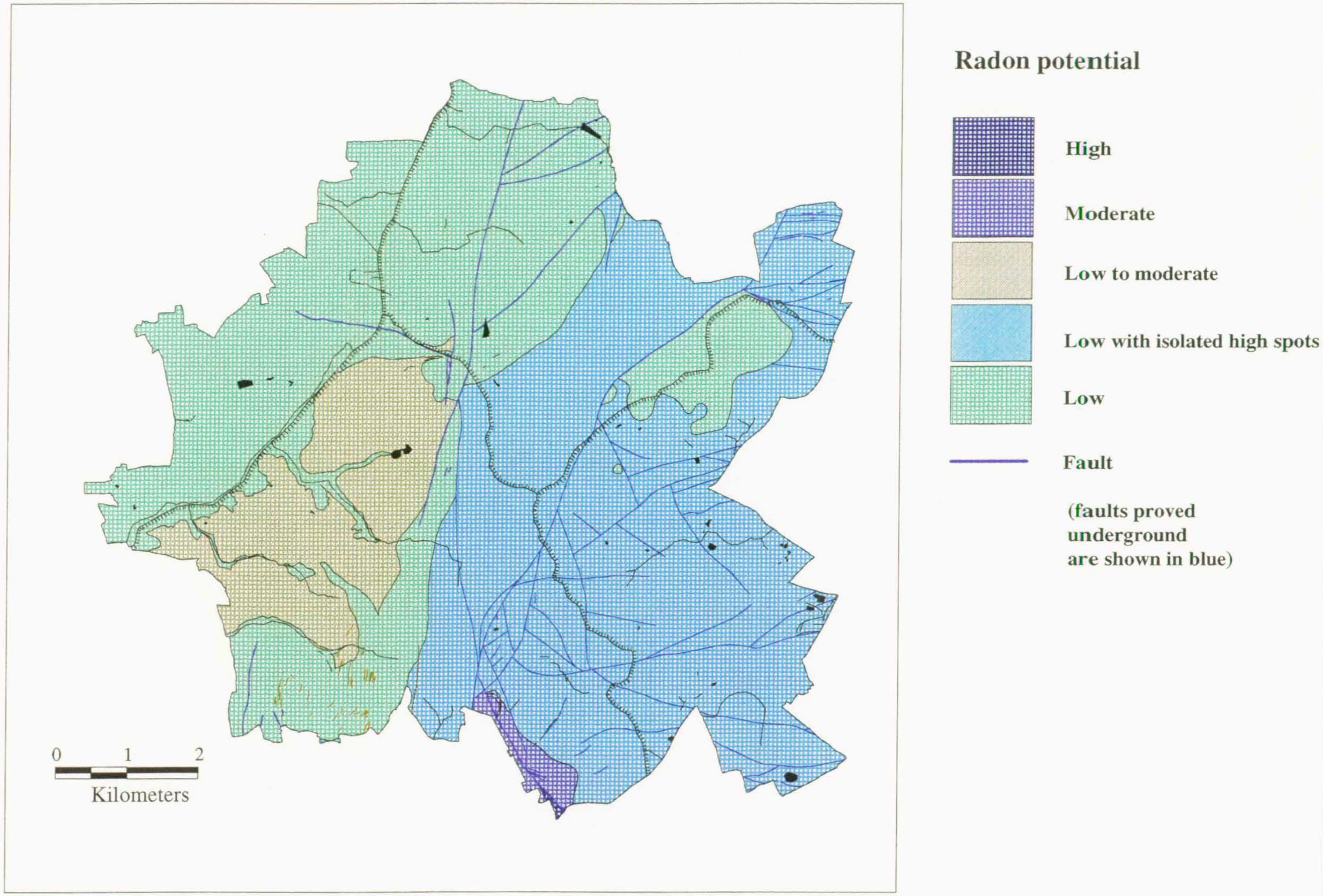


Figure 30 Radon potential map of the Borough

[30]

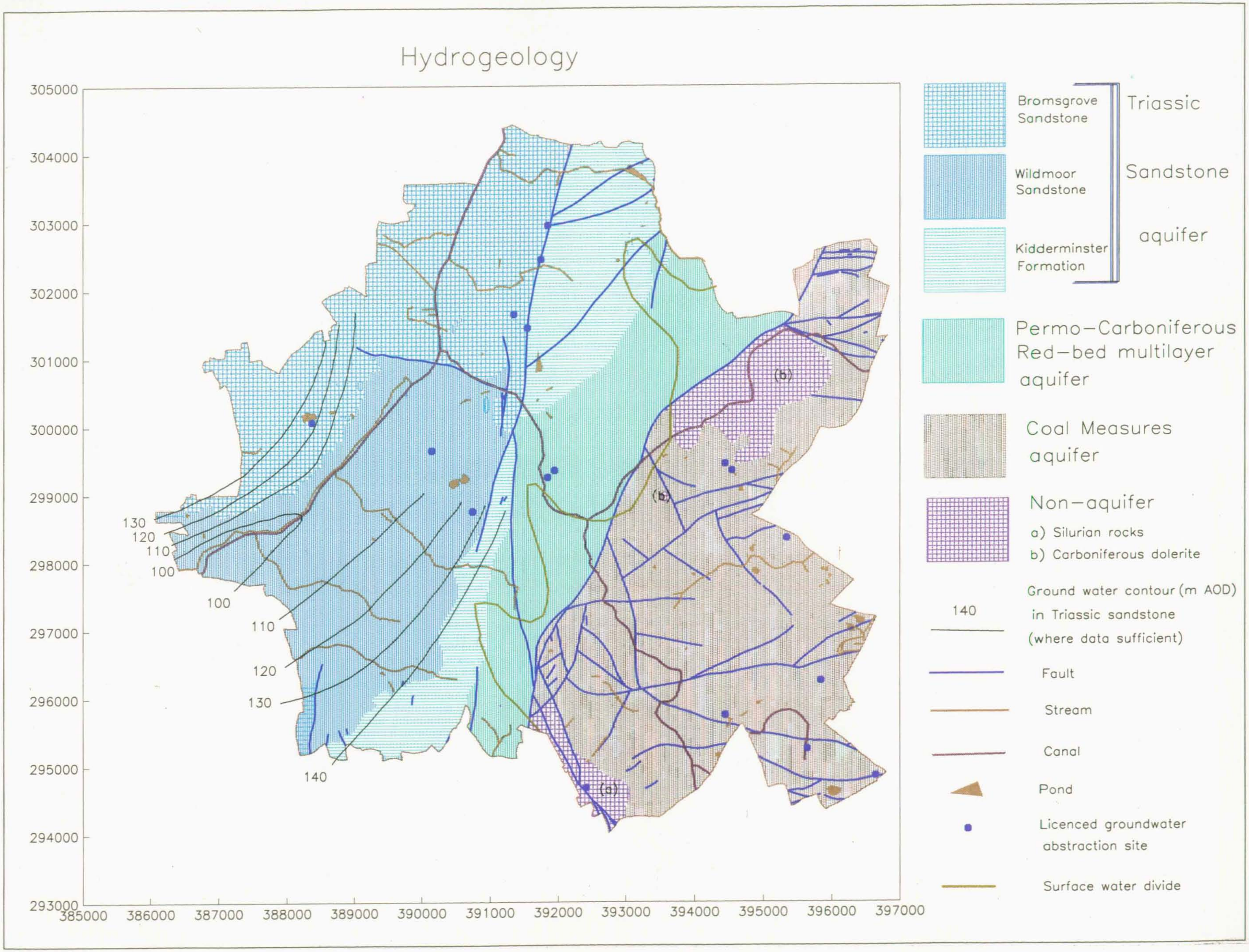


Figure 31. Hydrogeological map of the Borough showing the distribution of the main aquifers

[31]

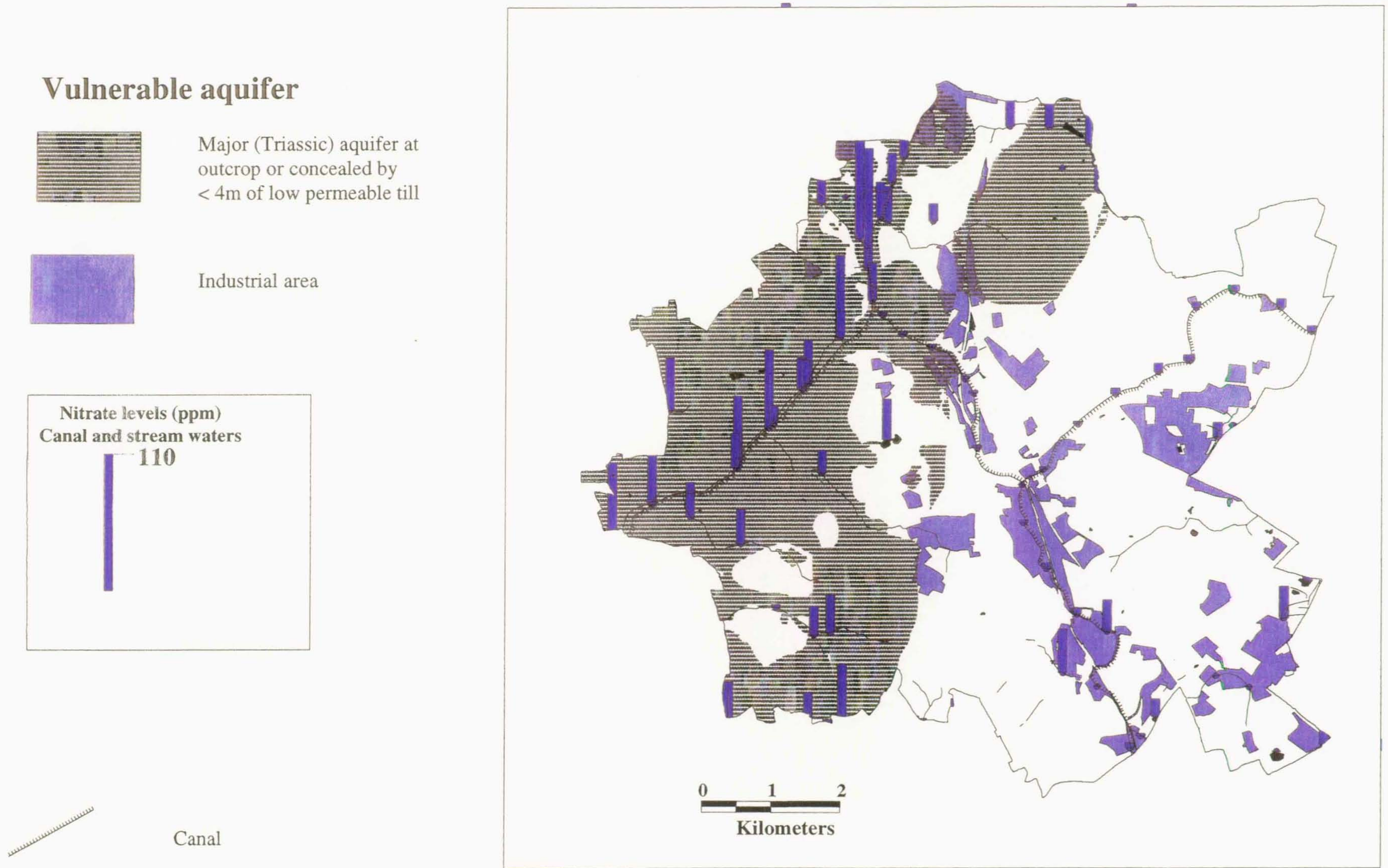


Figure 32. Aquifer vulnerability map

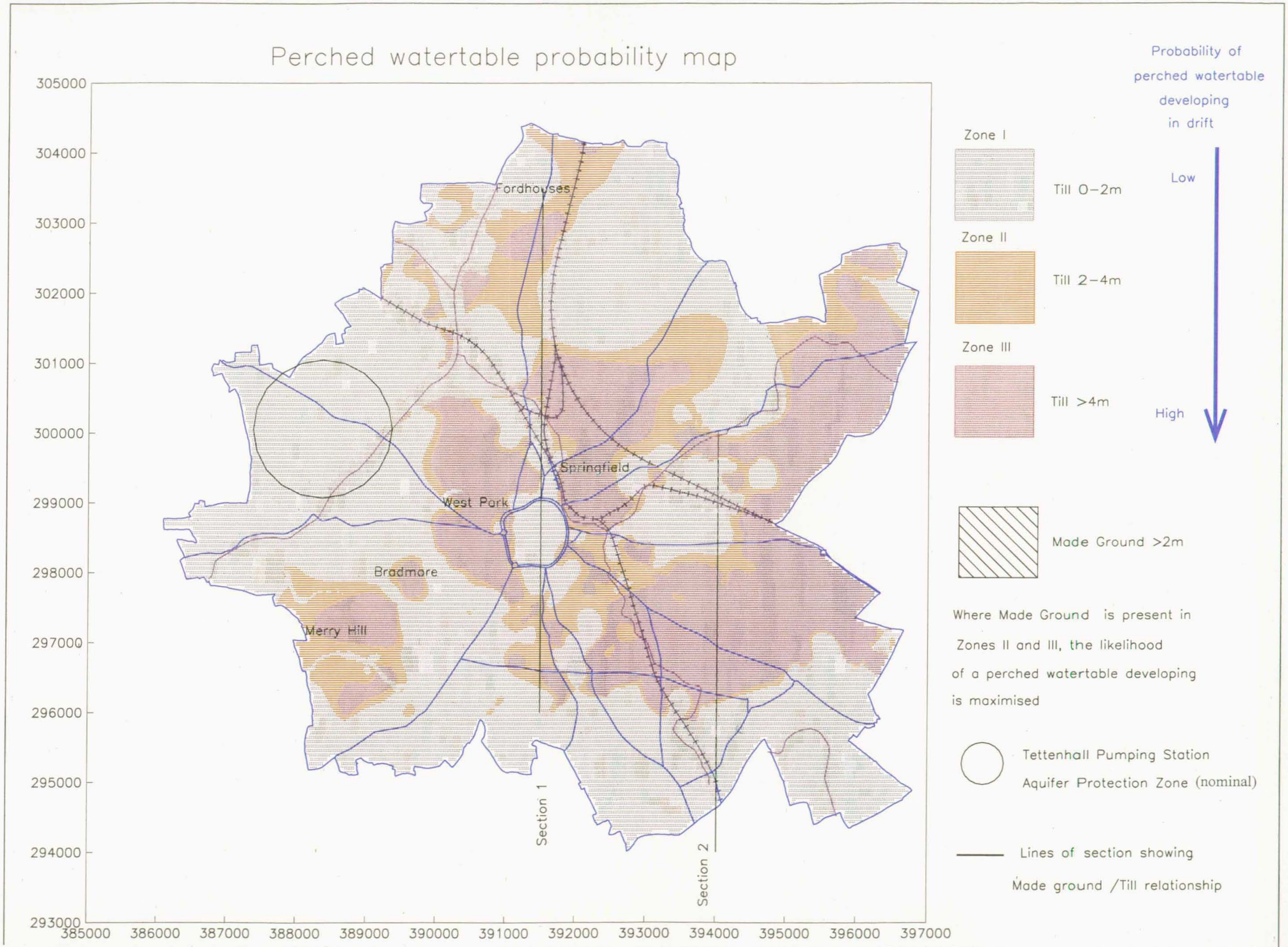


Figure 33. Perched watertable probability map

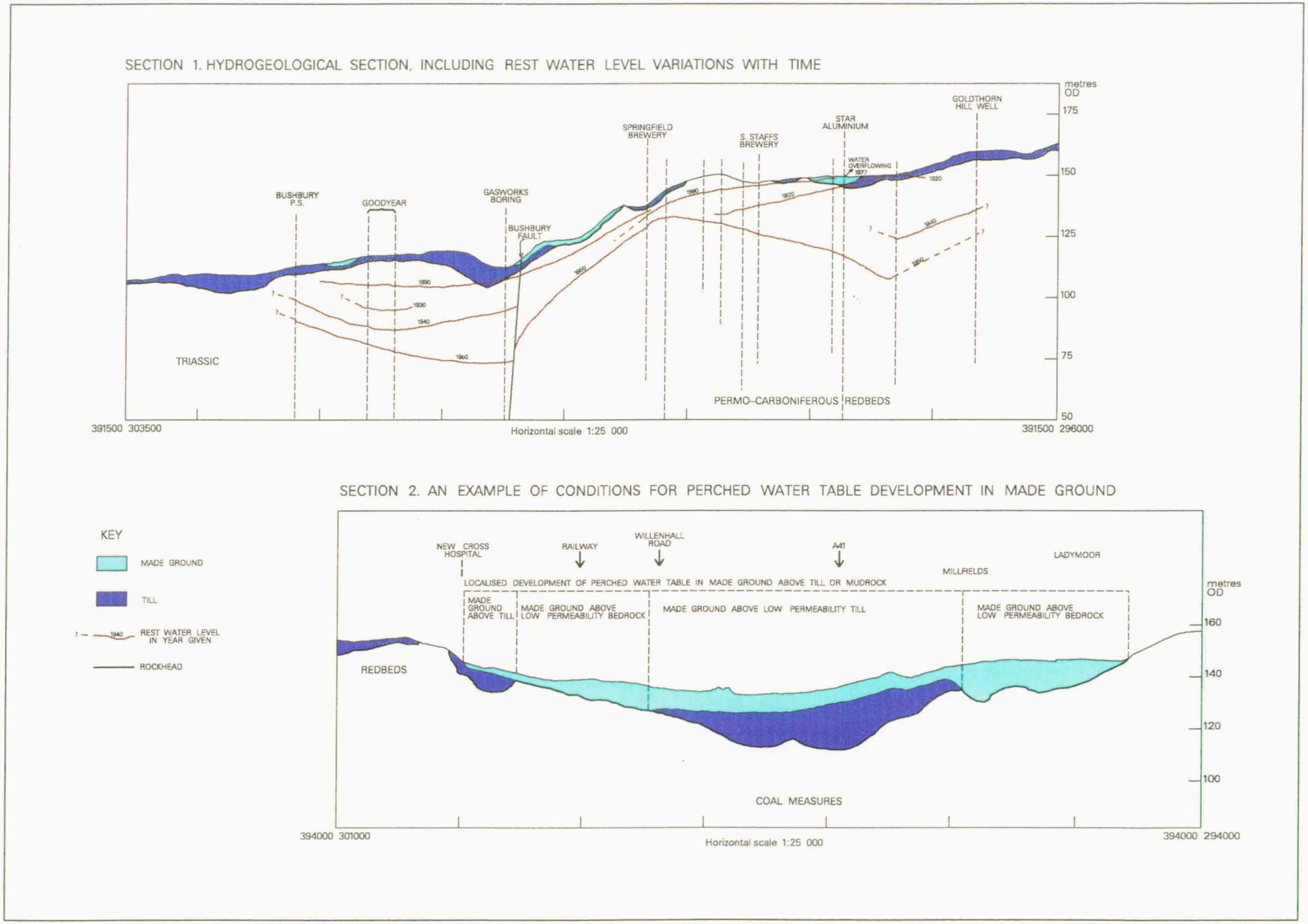
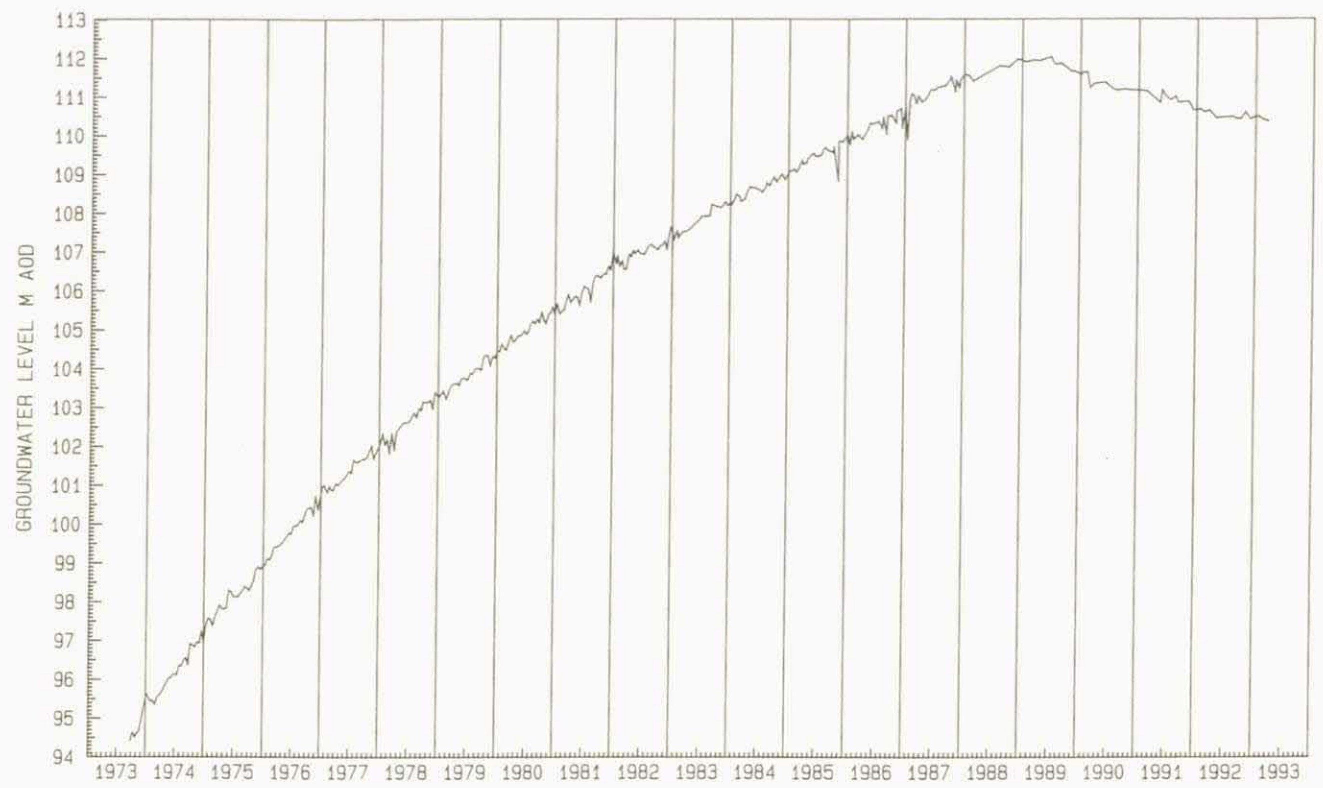
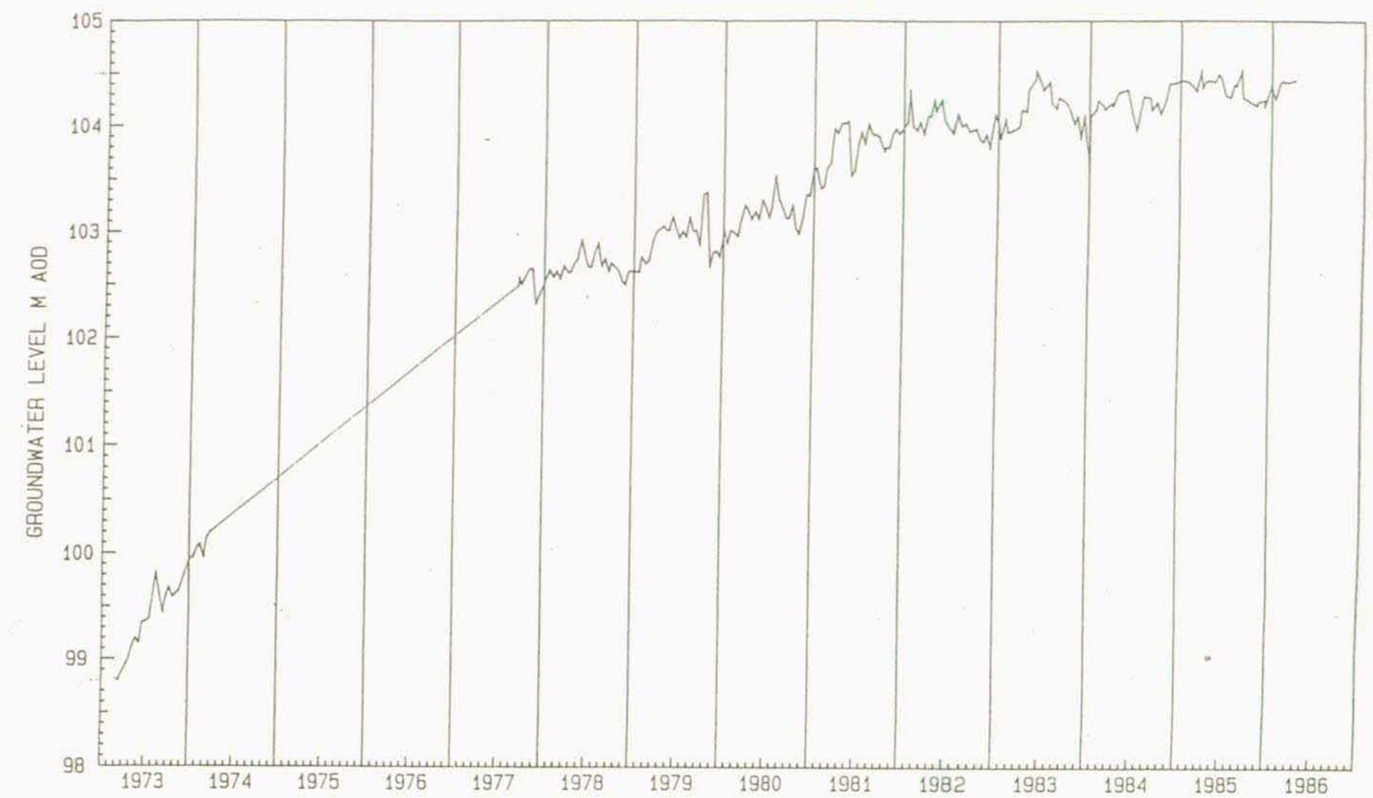


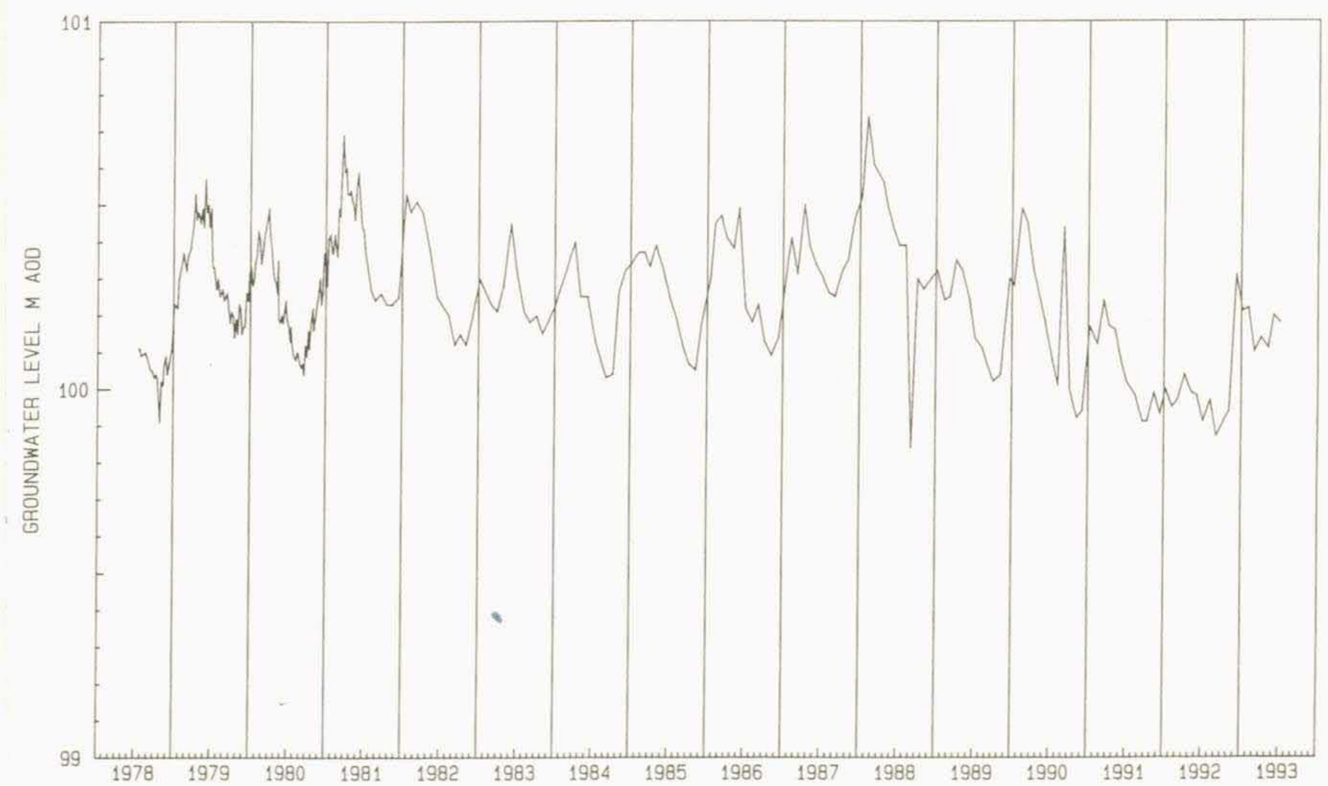
Figure 34. Hydrogeological sections through the superficial deposits



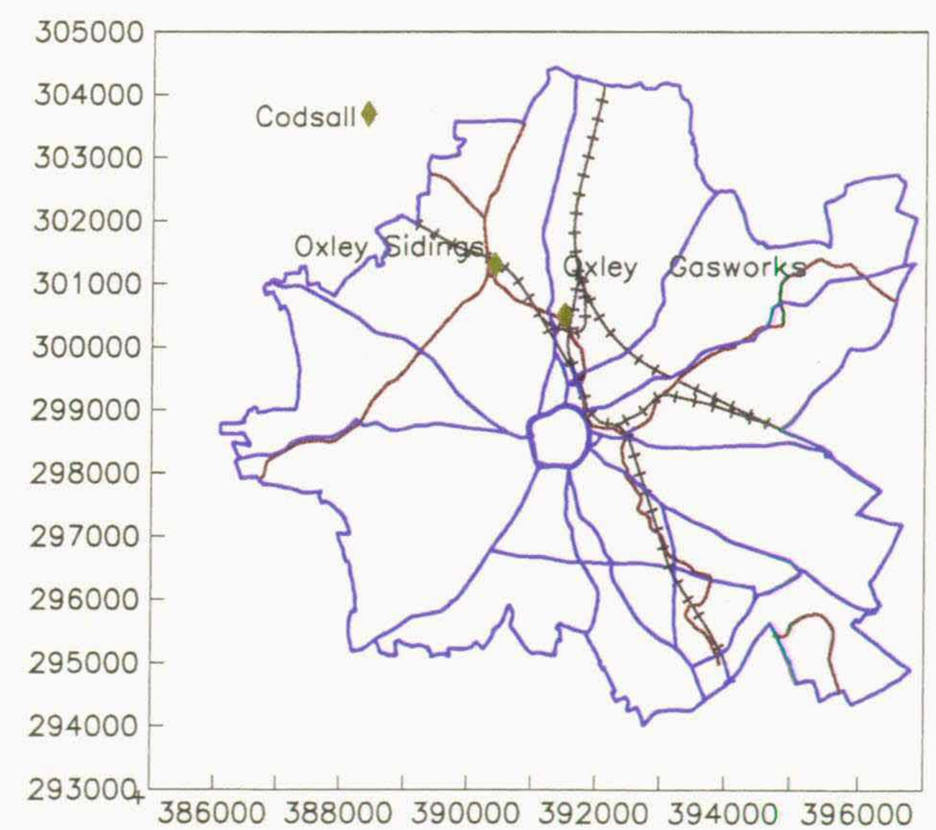
a) Oxley Gasworks



b) Oxley Sidings



c) Codsall



d) Location map

Figure 36. Hydrograph records for boreholes at a) Oxley Gas works b) Oxley Sidings c) Codsall

[36]

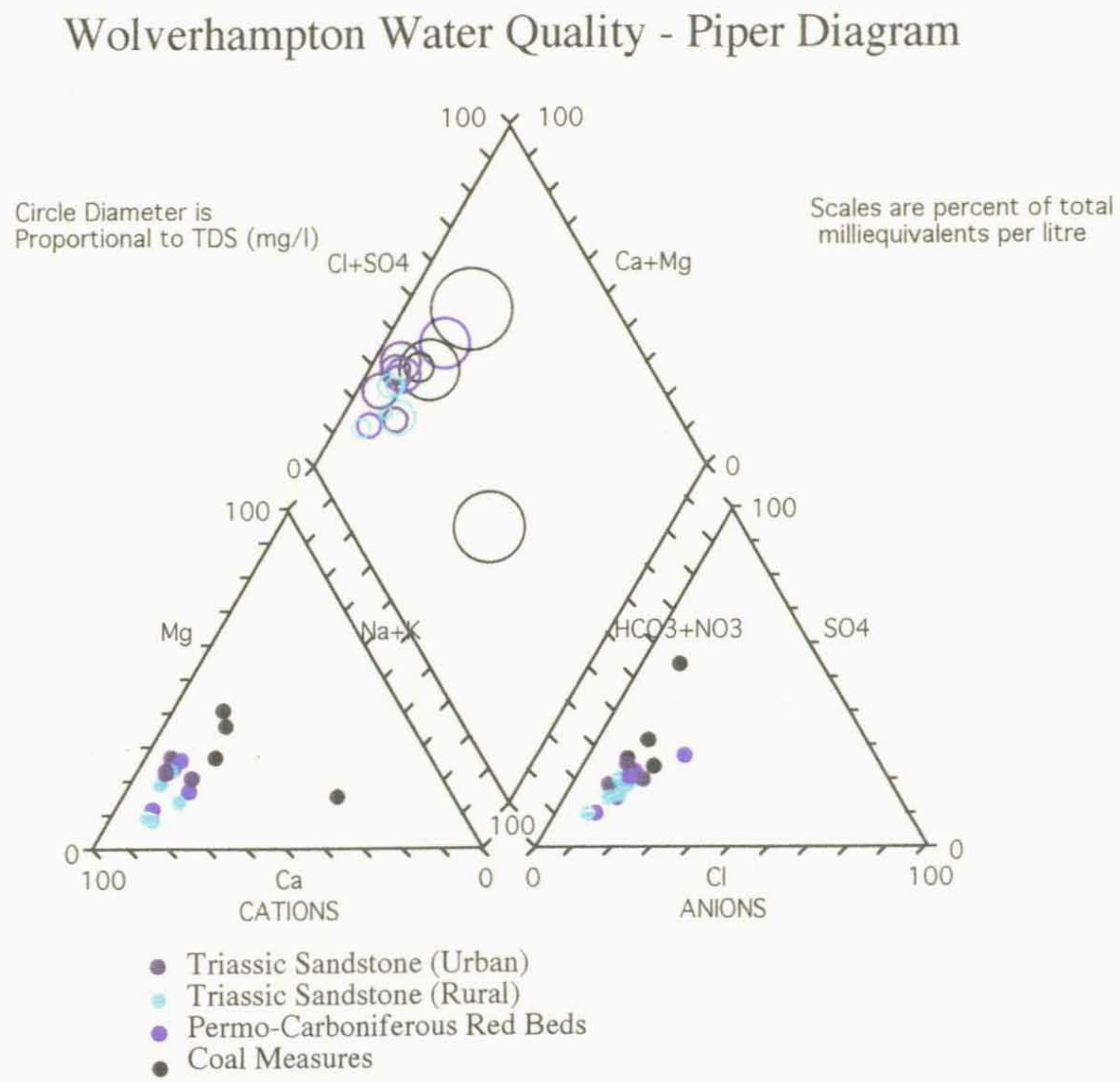


Figure 37. Wolverhampton water quality - Piper diagram

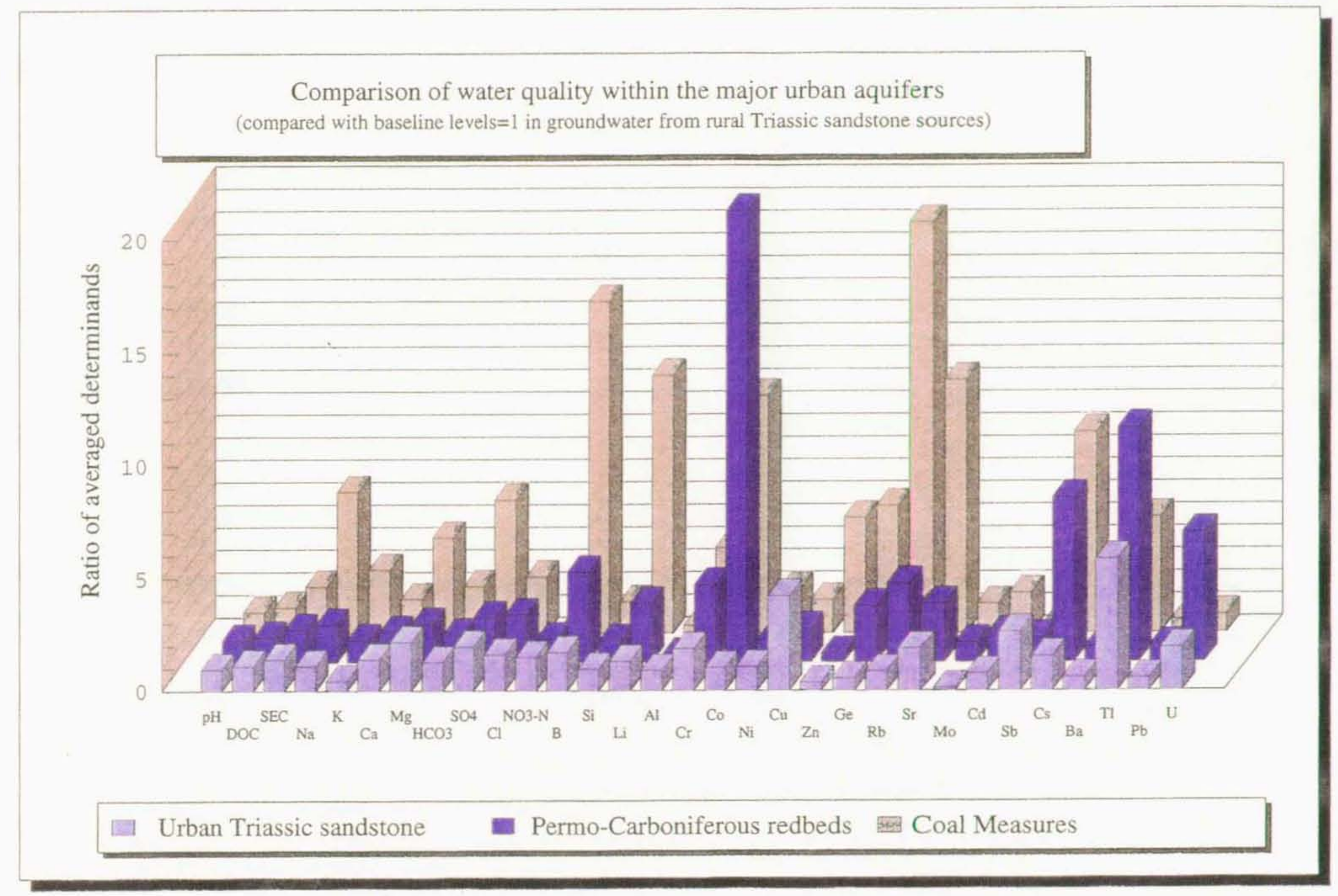


Figure 38. Variation in groundwater chemistry within the major urban aquifers

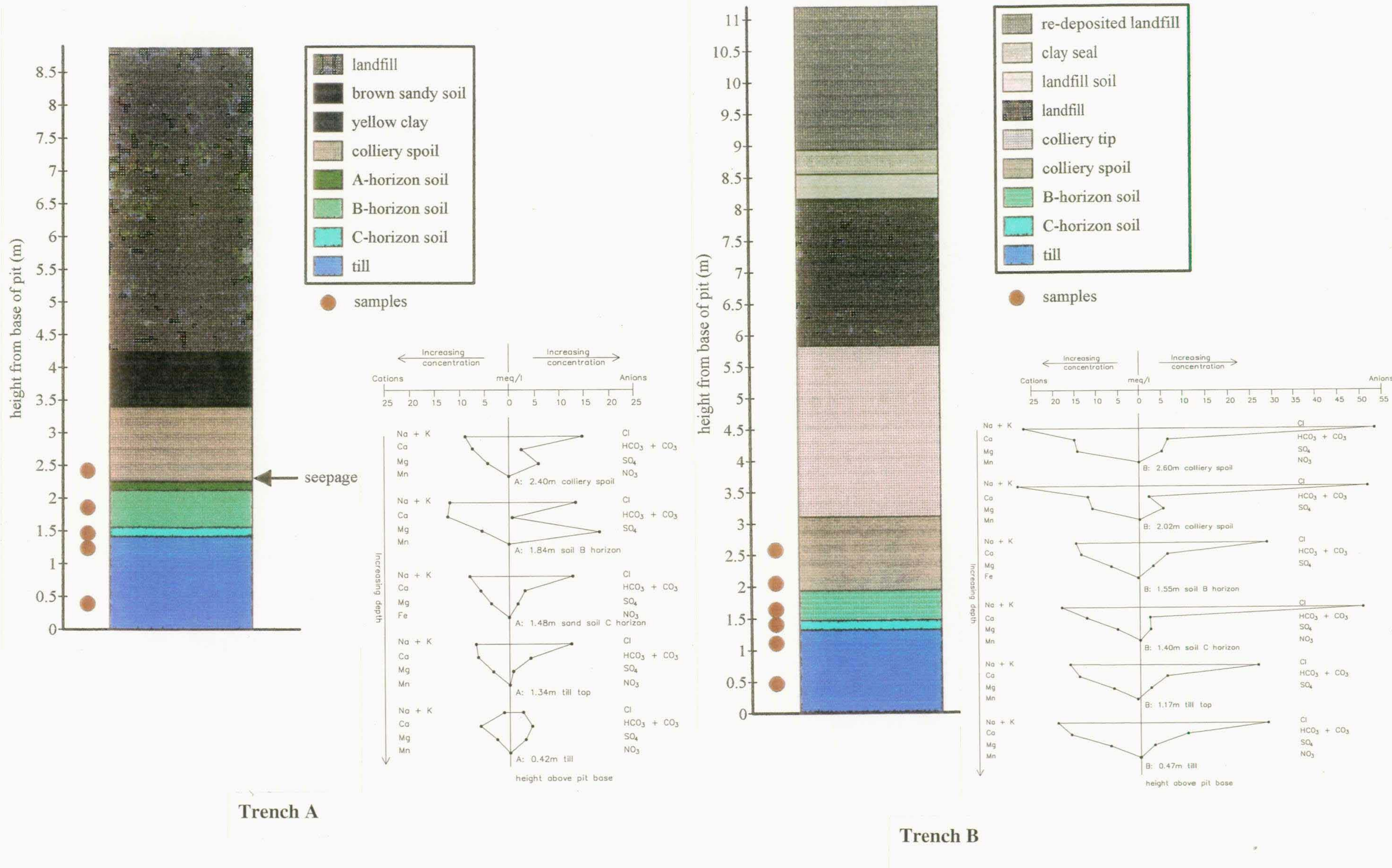
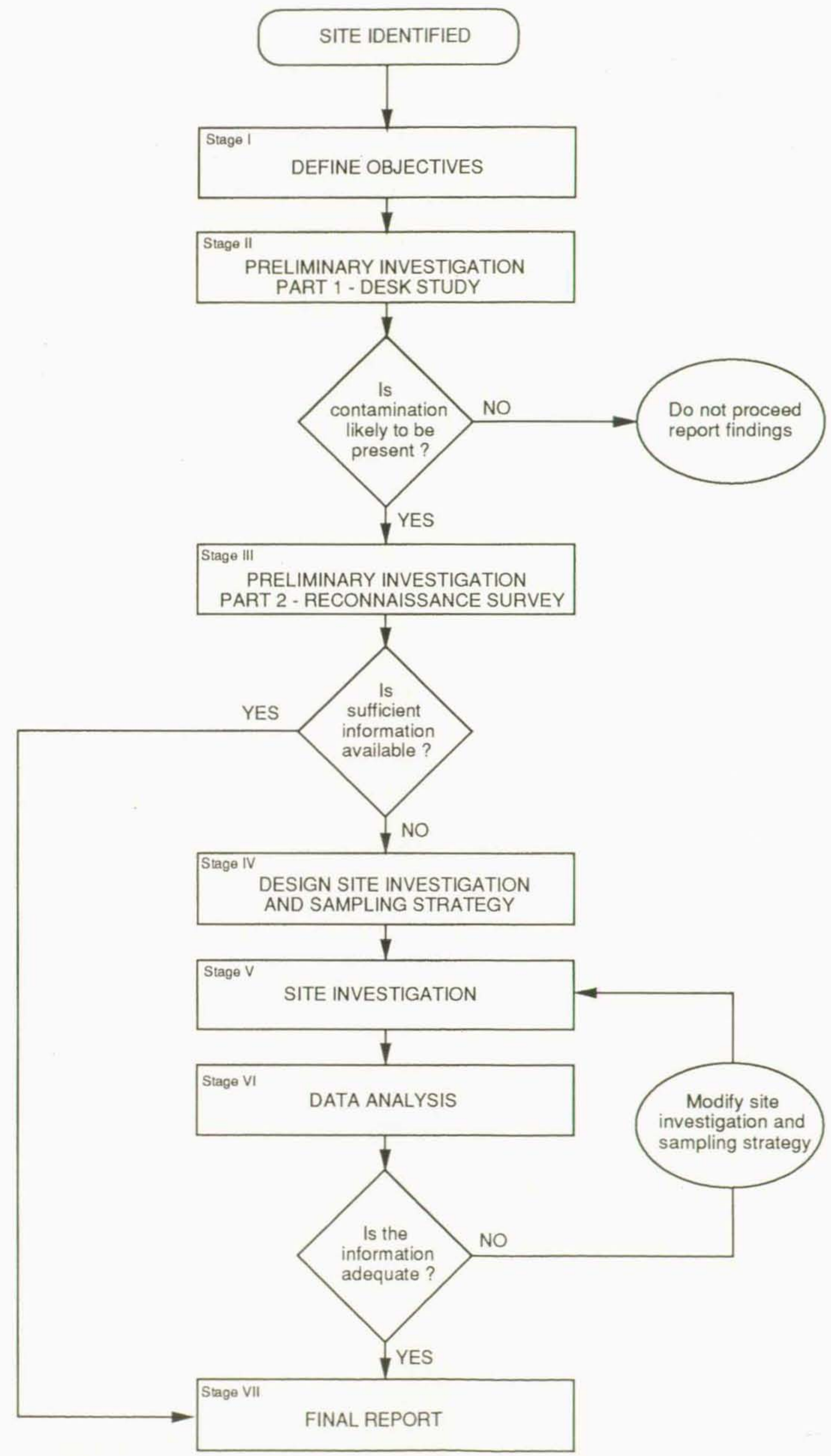


Figure 39. Lithological sections and stiff plots of major ion chemistry of pore water samples from Bowmans Harbour

[39]

Figure 40. Decision tree for the site investigation of the superficial (made ground) deposits at East Park, Wolverhampton

Decision Tree for the site investigation of East Park , Wolverhampton.



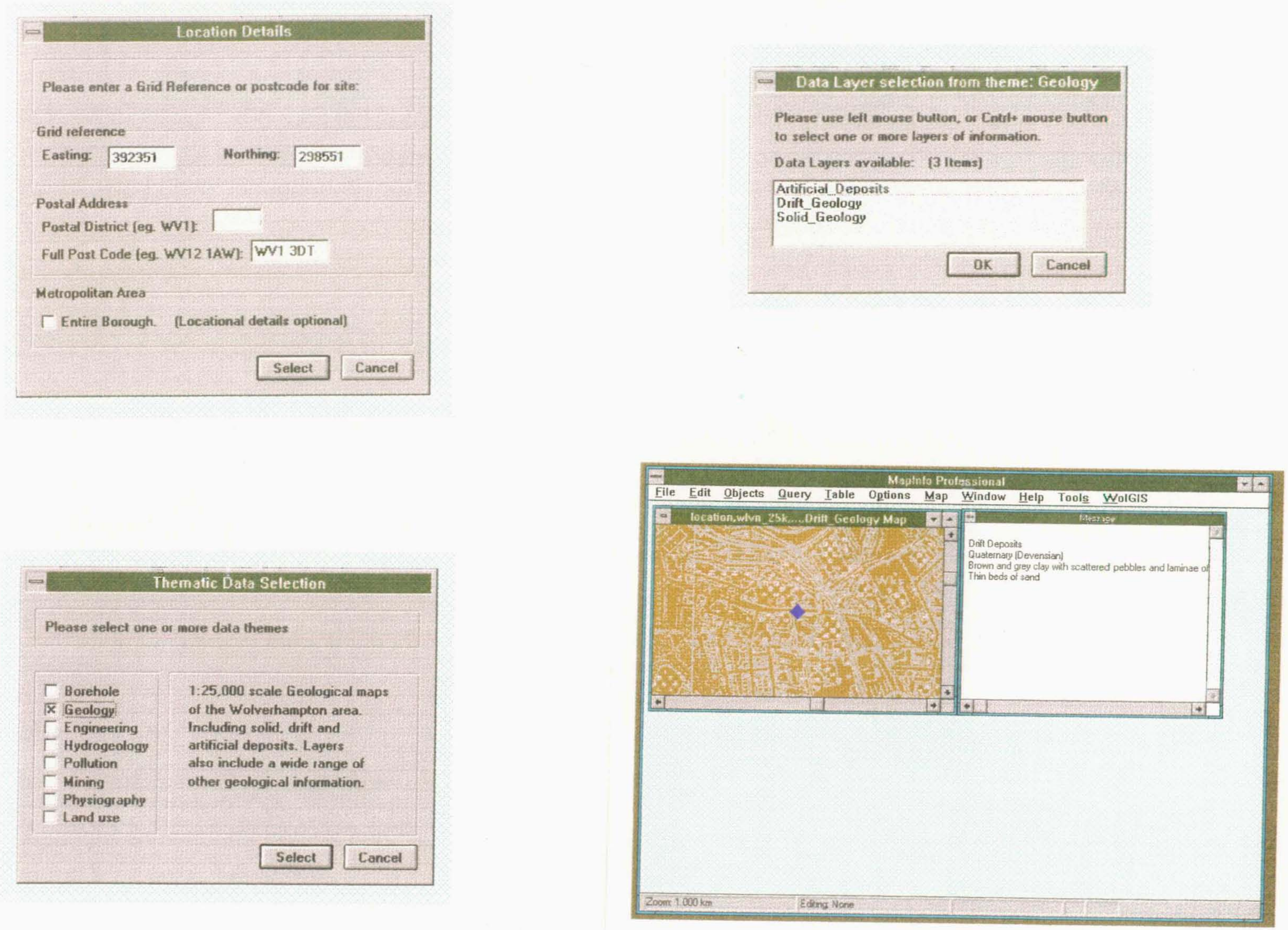


Figure 41. Menu panels displayed during a GIS query session.

[41]

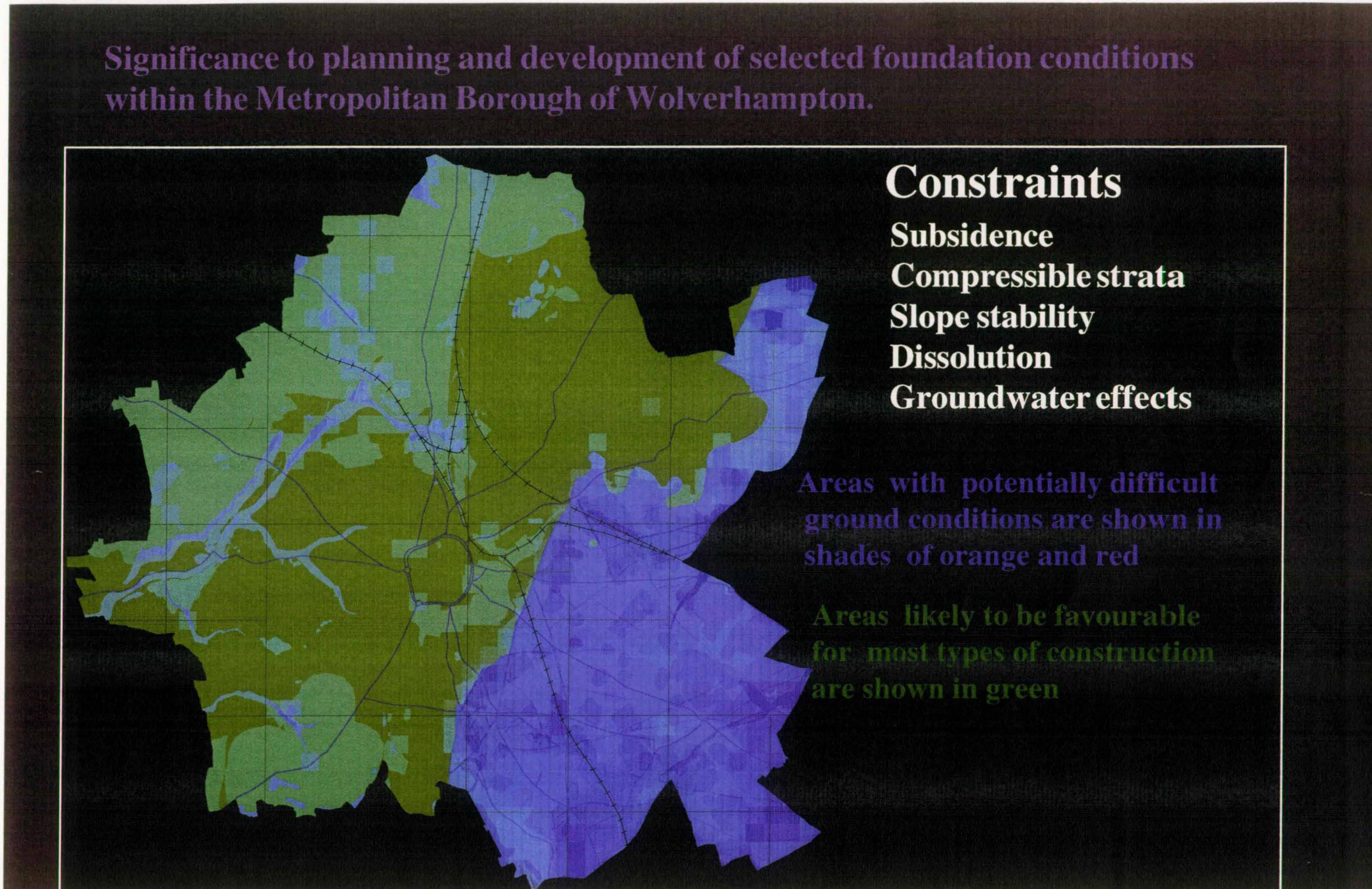


Figure 42. Significance to planning and development of selected foundation conditions within the Metropolitan Borough of Wolverhampton

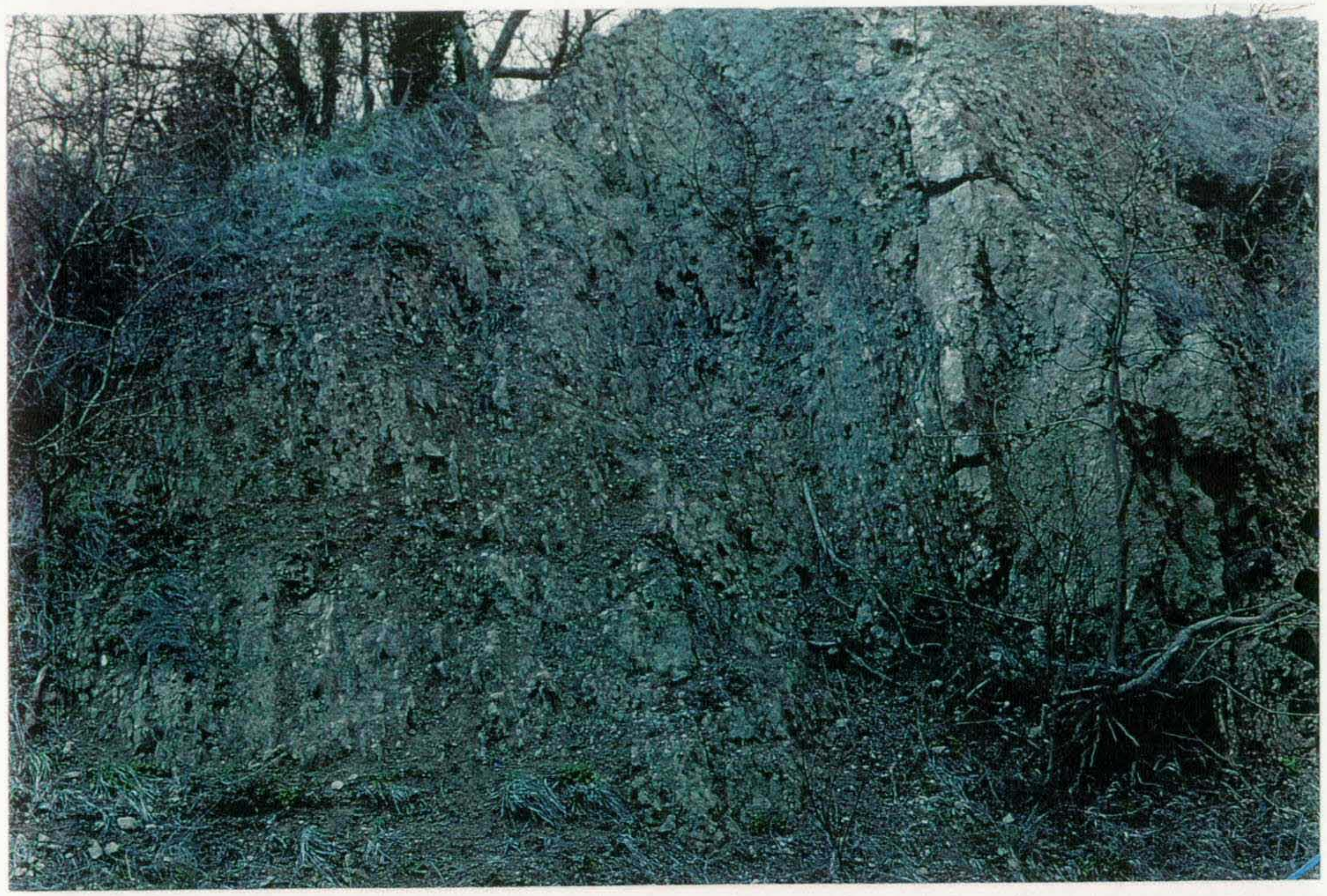


Plate 1a Steeply dipping Silurian limestones and mudstones within the Much Wenlock Limestone Formation, Gorge Road, Wolverhampton [9283 9409]. The Upper Quarried Limestone is visible in the right of the view.

Plate 1b Opencast workings within the Fireclay Coal seams at Bowman's Harbour [939 993]. The Coal Measures are overlain by reddish brown Devensian till and landfill (seen in background).

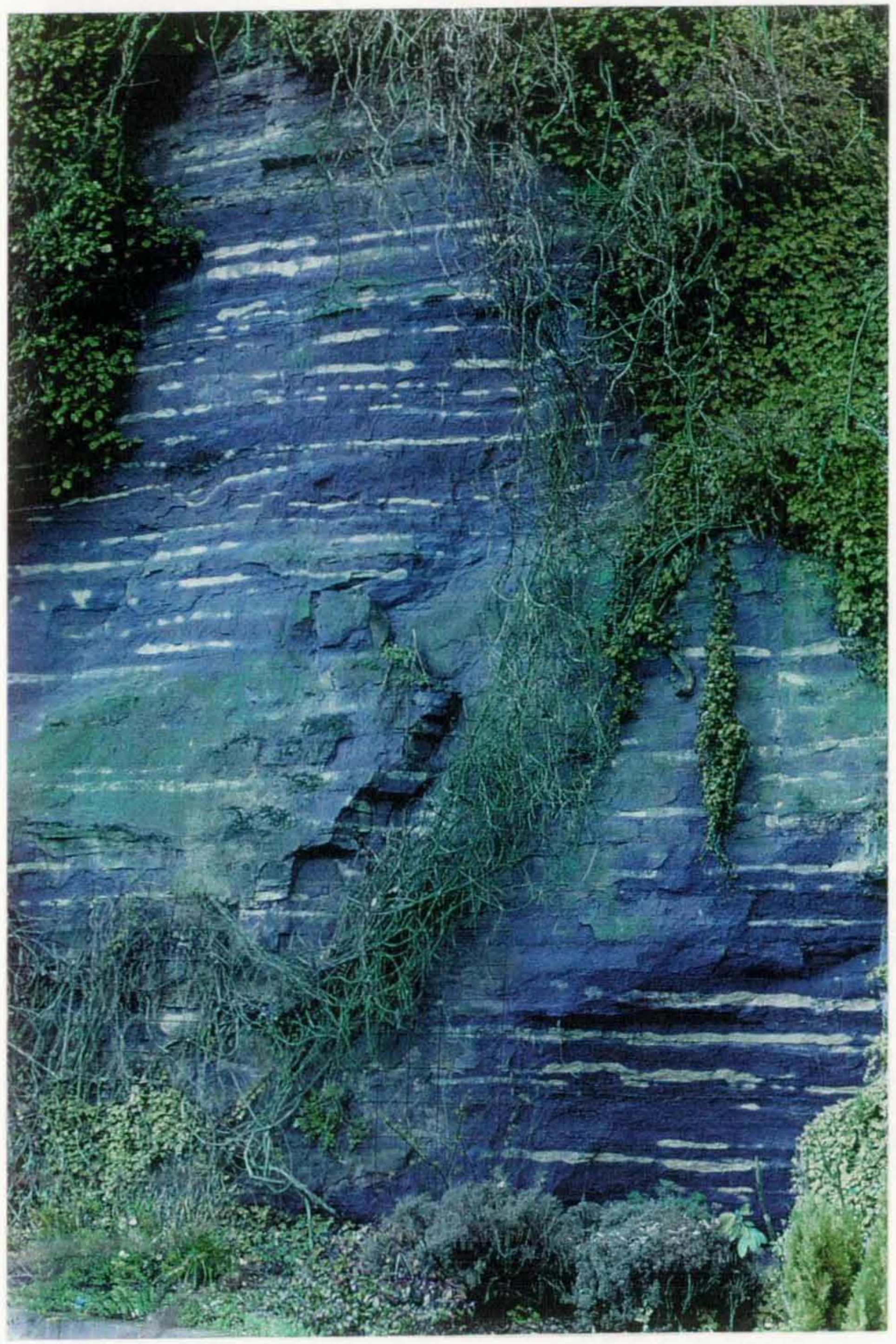


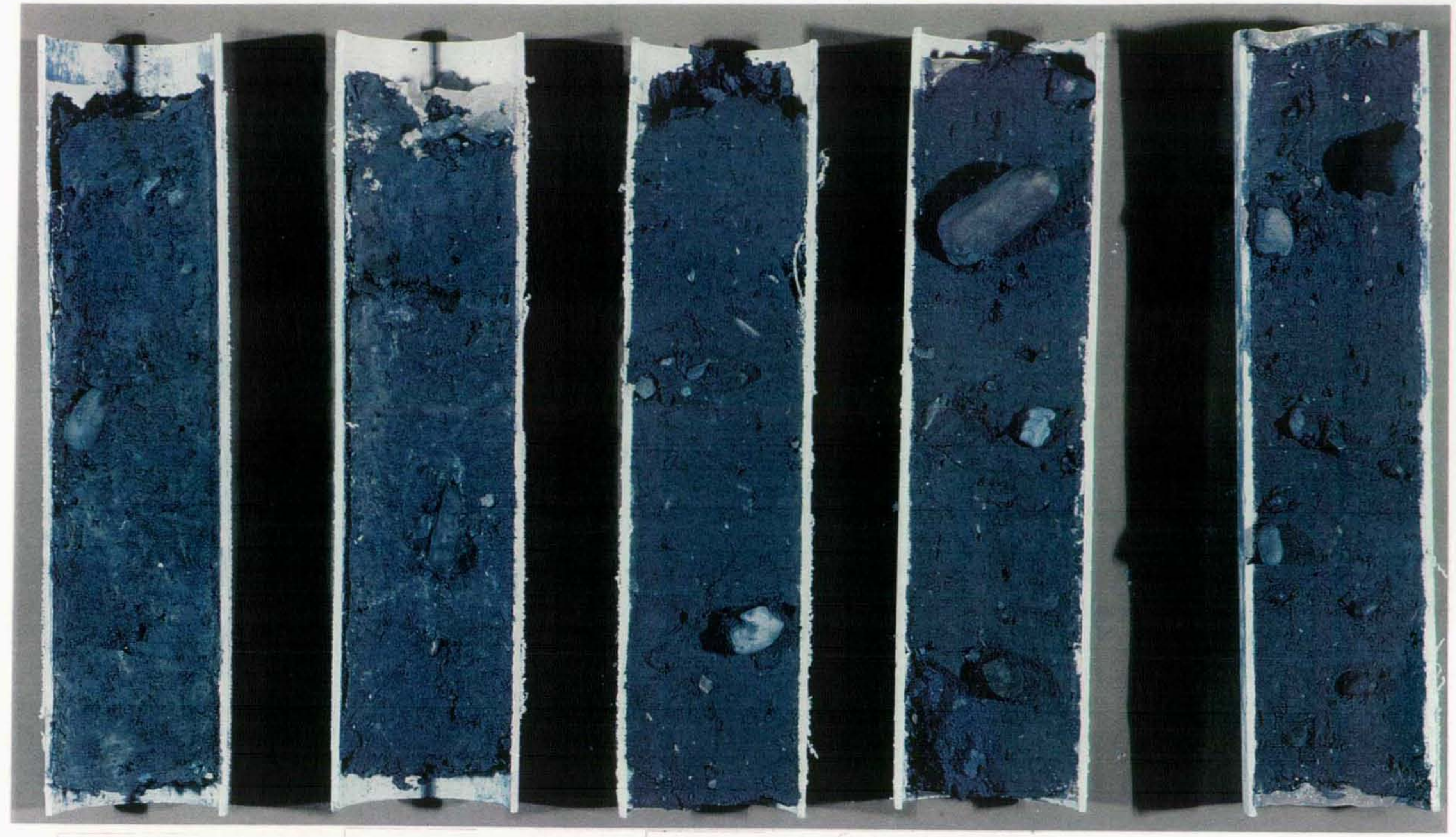
Plate 2a (above) Wildmoor Sandstone, The Gorge, Wolverhampton [8895 0010]. The ochreous red and grey colour banding is a distinctive feature of this formation.

Plate 2b (top right) Bromsgrove Sandstone exposed in railway sidings at Oxley Maintenance Depot, Wolverhampton [8895 0010]. Towards top of section, a pebbly sandstone unit defines a minor channel..

Plate 2c (bottom right) Close-up of pebbly channel sandstone seen in Plate 2b.

Plate 3 Samples (U100) of till with corresponding particle size data: Fowler Playing Fields Borehole [9204 0014].

Scale is 0.40m.



0.70-1.15 | 1.35-1.80 | 2.65-3.10 | 3.30-3.75 | 3.95-4.40