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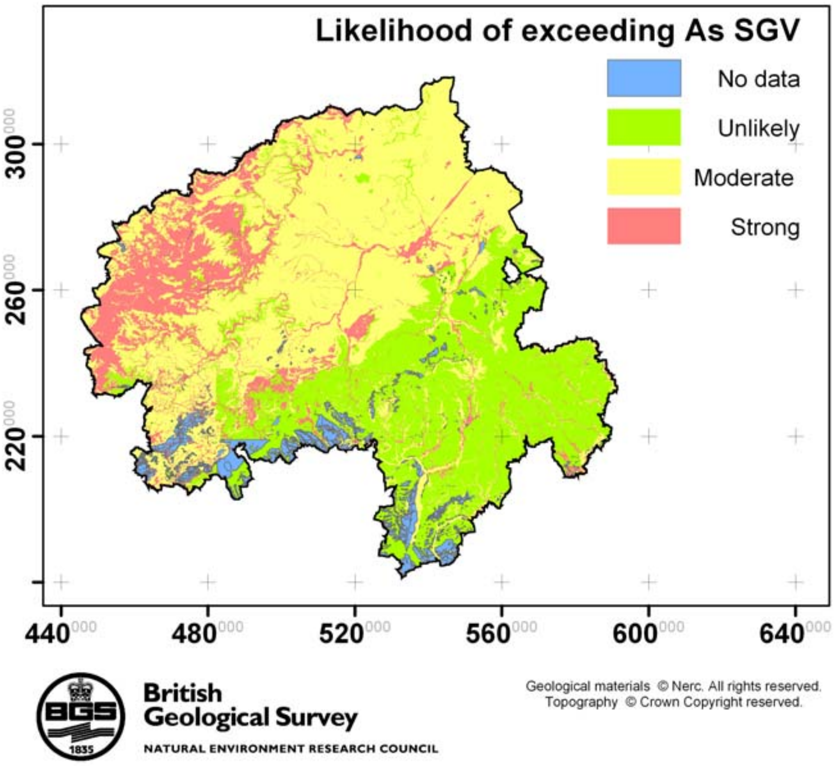
An appraisal of soil geochemistry for two growth areas in the south of England

Environmental Protection Programme

Commissioned Research Report CR/05/001N



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BRITISH GEOLOGICAL SURVEY

ENVIRONMENTAL PROTECTION PROGRAMME

COMMISSIONED RESEARCH REPORT CR/05/001N

An appraisal of soil geochemistry for two growth areas in the south of England

B Rawlins, A J M Barron and V Hulland

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Front cover

Image showing the likelihood of soil arsenic exceeding its Soil Guideline Value throughout the study region

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) undertaken on behalf of the Office of the Deputy Prime Minister.

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Contents

Foreword i

Acknowledgements i

Contents i

Summary iii

Rationale and approach iii

Confidence and likelihood predictions iii

1 Introduction 1

2 Theory 2

2.1 Controls on soil geochemistry 2

3 The study region and approach based on available data 4

3.1 Parent materials of the study region 4

3.2 Soil geochemical data from the G-BASE project 4

3.3 Stage 1 – Parent material types for which soil geochemical data are available 6

3.4 Stage 2 – Parent material types based on proxy soil geochemical data 7

3.5 Stage 3 – Lowestoft and London Clay formations - likelihood: classification based on proxy and published geochemical maps 8

3.6 Parent material types for which no data are available 8

4 Areas and uncertainty in likelihood classes 8

5 Likelihood map for arsenic 10

6 Likelihood map for nickel 11

Appendix 1 Summary of the 154 parent material types in the study region 13

Appendix 2 Summary arsenic and nickel soil geochemical data for parent material groups in the study region 16

Appendix 3 Summary arsenic and nickel soil geochemical data for parent material groups based on soil ‘proxy’ samples outwith the study region 18

References 19

FIGURES

Figure 1 - The study region growth areas - Milton Keynes and South Midlands (west) and London-Stansted-Cambridge (east) with shaded urban areas. Coordinates are metres of the British National Grid. 1

Figure 2 – Interpolated maps of topsoil geochemistry for the Humber-Trent region of the UK for a) As and b) Ni, based on around 6,500 sampling locations. The black lines delineate the major bedrock subdivisions. 3

Figure 3 – Maps of a) bedrock geology (green) without, and b) with, the overlying Quaternary deposits (purple) shown on top for part of the study region. The parent material map for the soil in this region is shown in image b). The image is based on 1:50,000 scale BGS maps of bedrock and superficial deposits.. 3

Figure 4 – Soil sampling locations from the G-BASE project for which analytical data are available in relation to the study region (black polygon). The available data comprise As and Ni concentrations for topsoil (0-15 cm depth; black symbols) and deeper soil (35-50 cm depth; red symbols). Coordinates are metres of the British National Grid. 5

Figure 5 - Long term continuity measured for arsenic using a soil reference material.................. 5

Figure 6 - Z-score performance for arsenic over four years of proficiency testing 6

Figure 7 - Soil sampling locations from the G-BASE project for which analytical data are available in an area outwith the study region (proxy data) but in which some of the parent material types occur. The available data comprise As and Ni concentrations for topsoil (0-15 cm depth; black symbols). Coordinates are metres of the British National Grid.................... 7

Figure 8 – Map showing the level of confidence in predicting likelihood of exceeding SGV’s throughout the study region. Coordinates are metres of the British National Grid................. 9

Figure 9– Map showing the likelihood of exceeding the residential SGV for As (arsenic) throughout the study region. Coordinates are metres of the British National Grid............... 10

Figure 10– Map showing the likelihood of exceeding the residential SGV for Ni (nickel) throughout the study region. Coordinates are metres of the British National Grid............... 11

TABLES

Table 1 – Likelihood classes for the mean concentration of trace elements in soils from the same parent material type for As and Ni 7

Table 2 – Levels of confidence in predicting likelihood of exceeding the SGV’s for As and Ni for the differing data availability across the study region 9

Table 3 – Likelihood of soil arsenic concentrations exceeding SGV (Table 1) throughout the study region and the total land area for each category 11

Table 4 – Likelihood of soil nickel concentrations exceeding SGV (see Table 1) throughout the study region and the total land area for each category 12

Summary

Rationale and approach

Soil geochemical data available from the BGS G-BASE (Geochemical Baseline Survey of the Environment) project has indicated that As (arsenic) and Ni (nickel) may be naturally elevated above their respective SGV's (soil guideline values) for residential land use over large areas of England. This does not imply that soil in these areas pose a significant risk to human health, but that considerable effort may be needed in undertaking risk assessments to determine whether there is the possibility of significant harm. To further their understanding of this potential problem, ODPM commissioned the British Geological Survey to generate maps covering the two growth areas (Milton Keynes/ South Midlands and London-Stansted-Cambridge), highlighting the likelihood of naturally elevated soil As and Ni concentrations exceeding their respective SGV's.

The assessment of baseline soil geochemistry presented in this report was based upon:

1. Soil geochemical data for As and Ni from the BGS G-BASE project
2. BGS 1:50,000 scale parent material (parent material) maps of the study region
3. Geochemical data from other published sources (including the Wolfson Geochemical Atlas and National Soil Inventory)

We adopted a three-stage approach to classifying the parent material polygons into the likelihood of the soil developed from them exceeding the SGV's for As and Ni; the three likelihood classes are: unlikely, moderate likelihood and strong likelihood. The first stage relates to those parent material types for which soil geochemical data are available. The second stage concerns those areas where soil geochemical data is not available for parent material types within the study region, but such data exists immediately outwith the study region. Hence, we have used these data as a proxy to classify the parent material types in the study region. Third, for areas where no BGS soil geochemical data exists within or outwith the region, we have used representations of geochemical data from the Wolfson geochemical atlas to classify these parent material types.

The outputs from the study were three GIS layers depicting:

1. the confidence we have in our predictions of likelihood for exceeding the SGV's
2. the likelihood (unlikely, moderate, strong) of exceeding the As SGV for residential land use (20 mg/kg)
3. the likelihood (unlikely, moderate, strong) of exceeding the Ni SGV for residential land use (50 mg/kg)

Confidence and likelihood predictions

We have a high level of confidence in our prediction of the likelihood of exceeding the SGV's for As and Ni for around three-quarters of the total land area. For around half the total land area there is a moderate likelihood that the As SGV for residential land use will be exceeded. More importantly, there are a series of parent material types covering around 15% of the total land area generally in the north and west of the study region over which soils have a strong likelihood of exceeding the 20 mg/kg As SGV for residential land use. Considerable funding may be required in undertaking site-specific risk assessments in these areas prior to residential development. For 40% of the total land area, generally over the central and western areas of the study region, there is a moderate likelihood that the Ni SGV for residential land use will be exceeded.

Where there is no data available for unique parent material polygons that cover only small parts of the growth areas, they were classified ‘no data’. If these occur in areas considered important in terms of future development, it would be relatively inexpensive to establish the likelihood of the soil exceeding the SGV’s for As and Ni by undertaking a limited amount of further soil sampling and analysis.

1 Introduction

The Deputy Prime Minister announced in July 2002 that there was potential for 200,000 homes to be provided additional to current plans by 2016. Much of this growth will be contained in the growth areas identified in regional planning guidance for London and the rest of South East England. These areas include the already established Thames Gateway and the three new growth areas of the Milton Keynes/South Midlands, London-Stansted-Cambridge (see Figure 1) and Ashford.

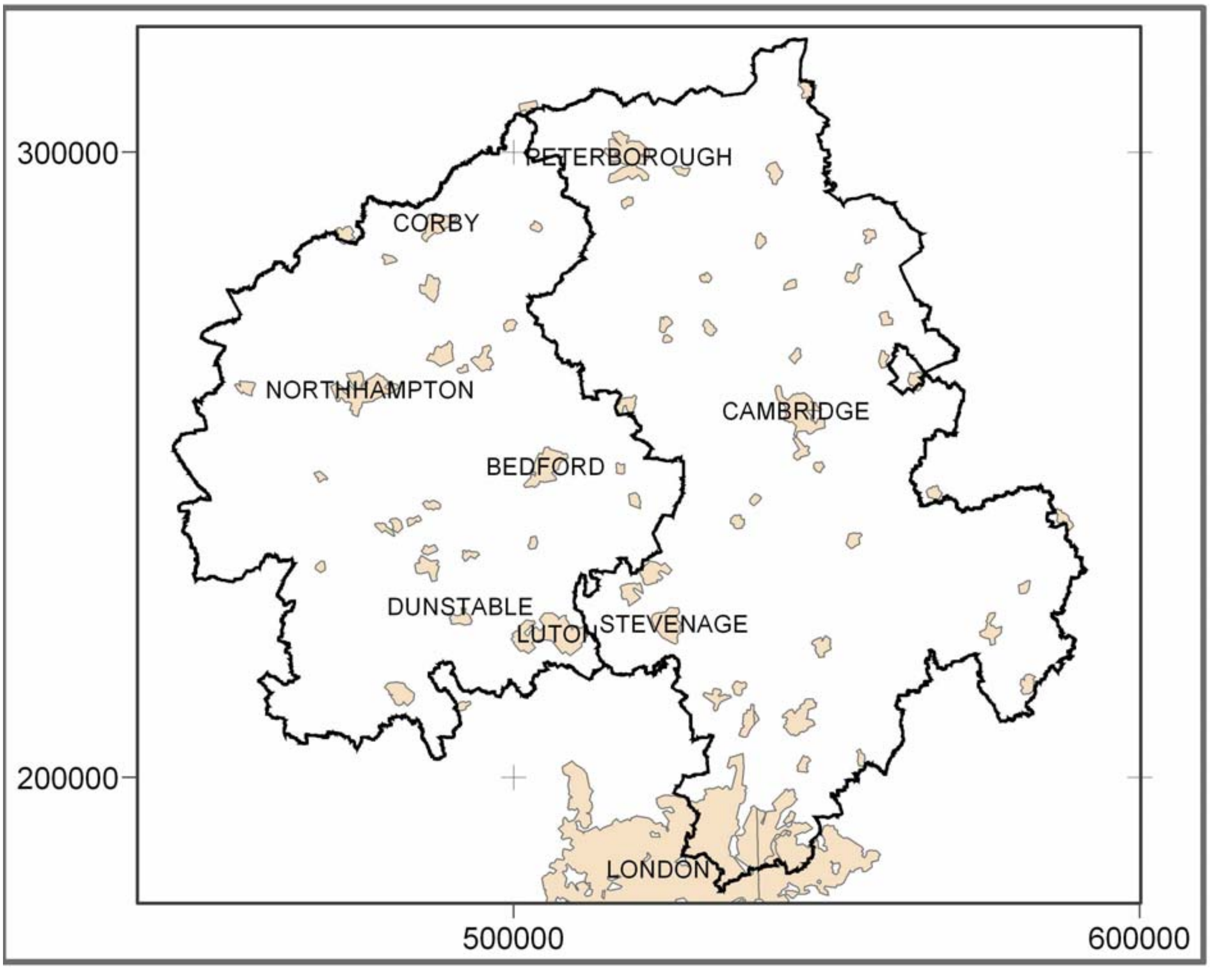


Figure 1 - The study region growth areas - Milton Keynes and South Midlands (west) and London-Stansted-Cambridge (east) with shaded urban areas. Coordinates are metres of the British National Grid.

The British Geological Survey have reported previously (Rawlins et al., 2002) that As (arsenic) may be naturally elevated above the SGV (soil guideline value) of 20 mg/kg for residential land use in parts of England (Department of the Environment Food and Rural Affairs and the Environment Agency, 2002a). This does not imply that soils in these areas pose a significant risk to human health, but that considerable effort may be needed in undertaking risk assessments to determine whether there is the possibility of significant harm. Soil nickel (Ni) concentrations also tend to be naturally elevated in these same areas and may also be present at concentrations above the SGV of 50 mg/kg (Department of the Environment Food and Rural Affairs and the Environment Agency, 2002b).

To further their understanding of this potential problem, ODPM commissioned the British Geological Survey to generate maps covering two of the growth areas (Milton Keynes/South Midlands and London-Stansted-Cambridge), highlighting the likelihood of naturally elevated soil As and Ni concentrations exceeding their respective SGV's for residential land use. The assessment of baseline soil geochemistry presented in this report was based upon:

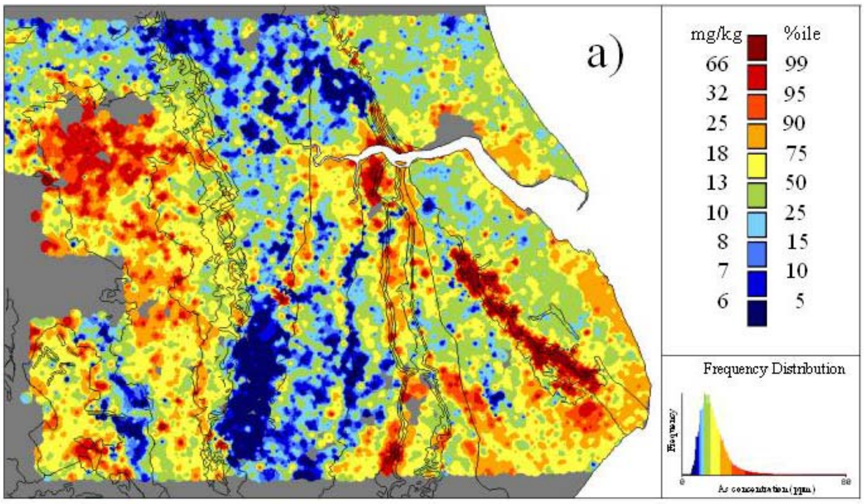
4. Soil geochemical data for As and Ni from the BGS G-BASE (Geochemical Baseline Survey of the Environment) project
5. 1:50,000 scale parent material maps of the study region
6. Geochemical data from other published sources (including the Wolfson Geochemical Atlas (Webb et al., 1978) and National Soil Inventory (Oliver et al., 2001).

The aim of this report is to describe how the above were used to create two layers in a GIS (Geographical Information System) predicting the likelihood of exceeding the SGV's for As and Ni respectively, throughout the study region. In addition, a layer was produced showing the level of confidence we have in our predictions. This currently (January 2005) varies because soil geochemical data for these elements is only available for around 60% of the study region. These three GIS layers were provided to OPDM in ArcMap 8.3 format as deliverables accompanying this report.

2 Theory

2.1 CONTROLS ON SOIL GEOCHEMISTRY

There are two main groups of factors that determine the natural geochemistry of soil; the parent material and its geochemical composition, and the weathering (pedogenic) processes that have transformed that material into the soil itself. Soils throughout England and Wales have developed from many kinds of bedrock and overlying Quaternary deposits, or a combination of the two where the latter are thin. The generation of soil geochemical maps by the British Geological Survey based on data from its G-BASE project, and statistical analysis of these data, has demonstrated that parent material is the primary control on topsoil geochemistry (Rawlins et al., 2003). For example, in the Humber-Trent region of the UK, parent material accounts for 36 and 32 % of the total variance of As (Figure 1a) and Ni (Figure 1b) respectively.



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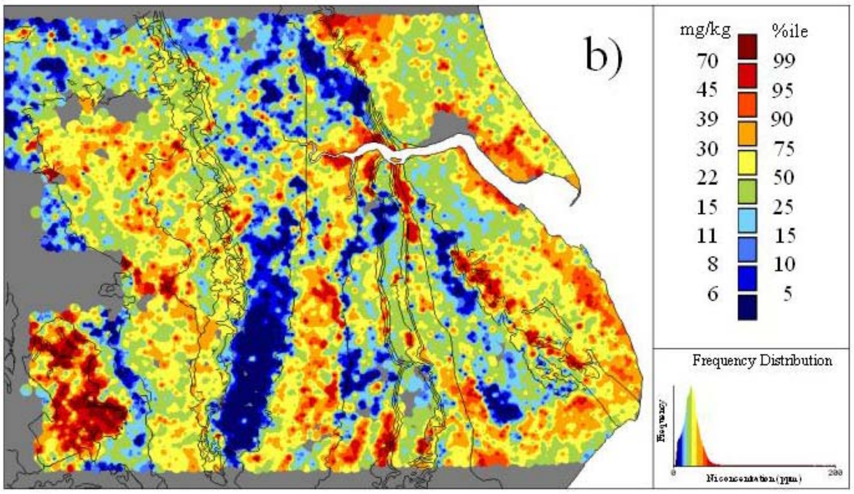

Figure 2 – Interpolated maps of topsoil geochemistry for the Humber-Trent region of the UK for a) As and b) Ni, based on around 6,500 sampling locations. The black lines delineate the major bedrock subdivisions.

Given the significance of parent material in determining the composition of the soil, the approach we have adopted in this report is based on partitioning the study region into intersecting parent material polygons, based on 1:50,000 scale maps of bedrock and Quaternary deposits. The natural, terrestrial landscape is comprised of bedrock, the solid rock that underlies loose material, such as soil, sand, clay, or gravel. In certain areas, soil is developed directly from the underlying bedrock. In such circumstances the bedrock is referred to as the parent material of the soil. In other parts of the landscape, loose superficial deposits occur above the bedrock. If a soil develops in such areas its parent material is this superficial material. By overlaying the distribution of superficial deposits above a map of the bedrock geology, we can create a continuous parent material map. This is illustrated in Figure 3.

We have adopted a three-stage approach to classifying the parent material polygons into the likelihood of the soil developed from them exceeding the SGV's for As and Ni; the three classes are: unlikely, moderate likelihood and strong likelihood. The first stage relates to those parent material types for which soil geochemical data are available. The second stage concerns those areas where soil geochemical data is not available for parent material types within the study region, but such data exists immediately outwith the study region. Hence, we have used these data as a proxy to classify the parent material types in the study region. Third, for areas where no BGS soil geochemical data exists within or outwith the region, we have used representations of geochemical data from the Wolfson geochemical atlas (Webb et al., 1978) to classify these parent material types.

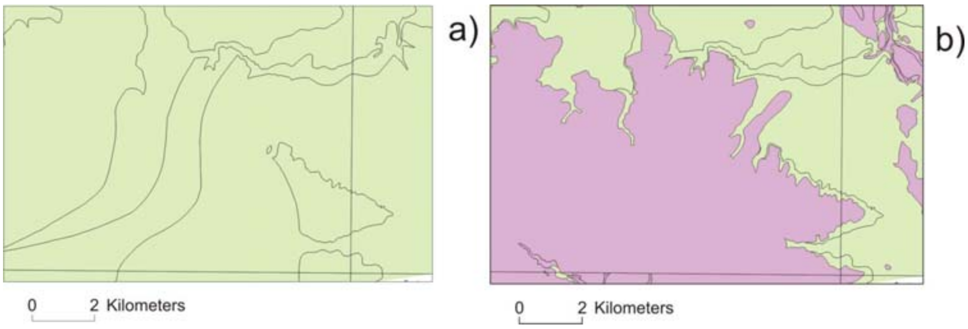

Figure 3 – Maps of a) bedrock geology (green) without, and b) with, the overlying Quaternary deposits (purple) shown on top for part of the study region. The parent material map for the soil in this region is shown in image b). The image is based on 1:50,000 scale BGS maps of bedrock and superficial deposits.

3 The study region and approach based on available data

3.1 PARENT MATERIALS OF THE STUDY REGION

A parent material map for the study region was generated by combining numerous BGS 1:50,000 scale digital maps of bedrock geology and superficial deposits of the study region, based on the method shown in Figure 3. This comprised 22,342 individual parent material polygons, of which there were 154 different parent material classes covering an area of 10,988 square kilometres. The names of the latter are listed in Appendix 1 along with a brief description of the nature of the material (e.g. clay, silt, sand, chalk etc.). Given the size of the growth areas and the complexity of the parent materials, it was not considered appropriate to reproduce a parent material map in this report as the resulting image would have been too detailed for meaningful interpretation. The reader should consult the regional geological guide for the majority of the study area (Sumbler, 1996) for further details of the parent material types.

3.2 SOIL GEOCHEMICAL DATA FROM THE G-BASE PROJECT

3.2.1 Background

The aim of the BGS G-BASE project is to produce baseline geochemical maps of inorganic elements in the surface environment of Great Britain using drainage sediment, surface soils and stream waters. The baseline can be used to identify and monitor changes to the environment caused by anthropogenic activity and long-term natural changes so as those brought about by climatic change. The G-BASE project is one of BGS's core survey projects that commenced in the late 1960's at which time it was primarily concerned with mineral exploration. It has now evolved into a multi-media, high-resolution geochemical survey producing geochemical baseline data relevant to many environmental issues. Samples are collected during the summer by teams of geoscience/environmental science undergraduates led by experienced BGS geochemists. All chemical analyses are done at the BGS laboratories in Keyworth with XRFS being the principal analytical method for stream sediments and soils.

3.2.2 Data availability

Soil geochemical data is available for approximately half of the entire study region, consisting of a total of 3095 samples (482 topsoil and 2613 deeper soil), shown in Figure 4.

3.2.3 Soil sampling, preparation and analytical methods

Sample sites for the soil were selected from every second kilometre square of the British National Grid by random choice within each square, subject to the avoidance of roads, tracks, railways, domestic and public gardens, and other seriously disturbed ground. At each site, topsoil (0-15 cm) is collected from five holes augered at the corners and centre of a square with a side of length 20 m with a hand auger and combined to form a bulked sample of around 1 kg. Deeper soil samples (35-50 cm) are also collected from the same auger holes and bulked to form a composite sample. All samples are archived at National Geoscience Data centre (Keyworth).

All topsoil samples of soil were dried, disaggregated, and sieved to pass through a 2 mm mesh. The deeper soil samples are sieved to sub 150 microns. All samples are air-dried at the laboratory prior to further preparation. All samples were coned and quartered and a 50 g sub-sample ground in an agate planetary ball mill until 95% was less than 53 µm. The pulverised material was further sub-sampled to obtain portions for analysis. A 12 g aliquot of milled material was mixed thoroughly with 3 g of binder for 3 minutes in an agate planetary ball mill. This mixture was then pressed into a 40 mm diameter pellet at 250 kN using a Herzog (HTP-40) semi-automatic press. The binder consists of 9 parts EMU120FD styrene co-polymer (BASF plc) and one part Ceridust 3620 a micronised polyethylene wax (Hoechst). Minor and trace element determinations for As and Ni were carried out by wavelength-dispersive X-ray fluorescence spectrometry (Ingham and Vrebos, 1994). The lower reporting limit for arsenic and nickel is 1 mg/kg.

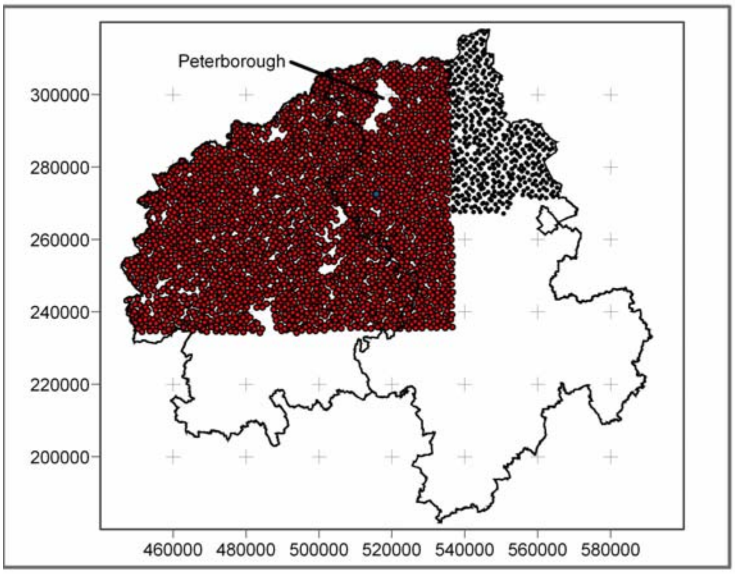

Figure 4 – Soil sampling locations from the G-BASE project for which analytical data are available in relation to the study region (black polygon). The available data comprise As and Ni concentrations for topsoil (0-15 cm depth; black symbols) and deeper soil (35-50 cm depth; red symbols). Coordinates are metres of the British National Grid.

3.2.4 Quality control

Batch to batch continuity is monitored by the analysis of six RMs (reference materials) at the beginning and end of the analysis of each batch of 500 samples. An example of the RMs is plotted in Figure 5 showing arsenic values for a soil RM measured for over three years. The results have ±3 sigma control limits of ±2.58 mg/kg but are better than the ±2 sigma warning limits of ±1.7 mg/kg. Each pellet is measured a maximum of five times on each face then a fresh aliquot is taken and a new pellet prepared.

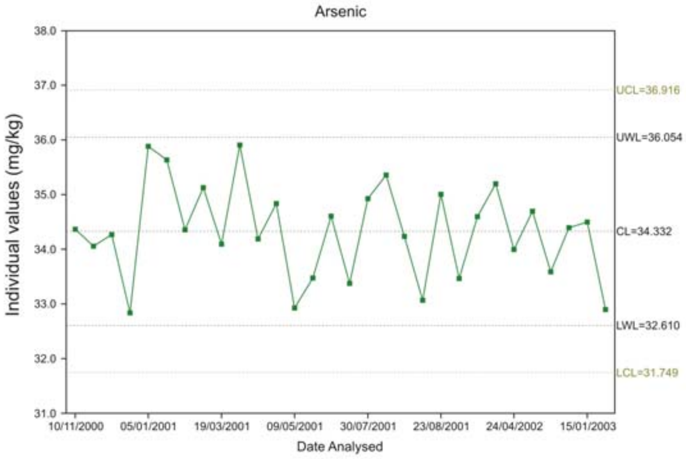

Figure 5 - Long term continuity measured for arsenic using a soil reference material

Quality Control (QC) is monitored by analysis of two silica glass samples spiked with a wide range of trace elements: BGS Low has trace element concentrations in the range 20-40 mg/kg and BGS High has trace elements concentrations in the range 250-350 mg/kg. One of these samples is analysed in approximately every 50 unknown samples.

QC charting and verification are carried out using control charts, onto which are plotted the mean and control and warning limits of the QC data. Sample data from an analytical run are not used if the QC data fall outside ±3sigma control limits or if two or more consecutive QCs fall outside ±2sigma warning limits, unless authorised by the XRFS laboratory manager. QC data are also monitored for drift and bias, and analytical data may not be used if the mean QC values for 10 out of 11 consecutive analytical runs fall one side of the mean, or if 8 consecutive mean QC values successively rise or fall. Any batches of samples governed by a failing QC sample are re-analysed.

3.2.5 Proficiency testing

The method is subjected to proficiency testing using the Wageningen Evaluating Programmes for Analytical Laboratories (WEPAL) International Soil-analytical Exchange (ISE) scheme. Soil samples are analysed on a regular basis and the data from these can be used to independently assess the accuracy of the method. To comply with the WEPAL regulations, the z-scores for the BGS data calculated by reference to all participating laboratories have to be less than three.

Figure 6 shows the z-score performance over four years for arsenic to be better than two. Points outside of two are explained on the graph.

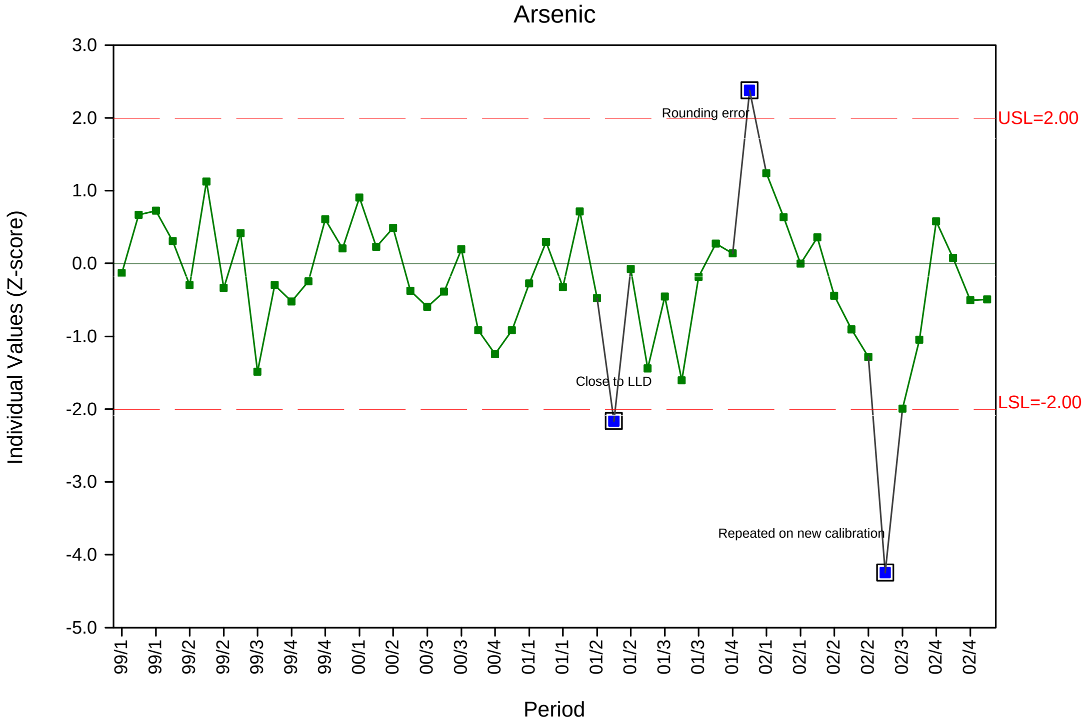

Figure 6 - Z-score performance for arsenic over four years of proficiency testing

3.3 STAGE 1 – PARENT MATERIAL TYPES FOR WHICH SOIL GEOCHEMICAL DATA ARE AVAILABLE

Where data are available in the study region (see Figure 4), we assigned each soil sampling location to a parent material type using a point-in-polygon GIS procedure. For those parent material types with more than five soil samples, we calculated the mean concentration of As and Ni for each type to indicate the likelihood of it exceeding the SGV according to the figures in

Table 1 below. For those parent material types with less than 5 samples, which cover a limited geographical area, we assessed each set of samples individually prior to assigning a likelihood class.

Table 1 – Likelihood classes for the mean concentration of trace elements in soils from the same parent material type for As and Ni

Likelihood class (map colour)	**mean As concentration (mg/kg) for parent material polygon**	**mean Ni concentration (mg/kg) for parent material polygon**
Unlikely (green)	<15	<40
Moderate likelihood (amber)	15-25	40-60
Strong likelihood (red)	> 25	>60

The parent material types for these soil samples, the number of soil samples acquired from them and the average concentrations of As and Ni are presented in Appendix 2. The parent material types that underlie these soil samples are those in which we have the greatest confidence in predicting the likelihood of exceeding the SGV's.

3.4 STAGE 2 – PARENT MATERIAL TYPES BASED ON PROXY SOIL GEOCHEMICAL DATA

Where soil geochemical data exists outside the study region for the same bedrock parent material types that occur within the study region, we used these data to predict the likelihood classes for the soil developed over the parent materials in the study region. Each bedrock parent material type was considered individually by the BGS regional geologist to assess whether the parent material within the study region was significantly different to the same unit from outside the region. Some bedrock parent material types that occur outwith the growth area are lithologically, and therefore geochemically, similar to the occurrence of the same parent material types within the growth area (e.g. the Gault Formation, the Zig-Zag Chalk Formation). For those parent material types considered to be quite different, this was taken into account in assigning the likelihood classes in Table 1.

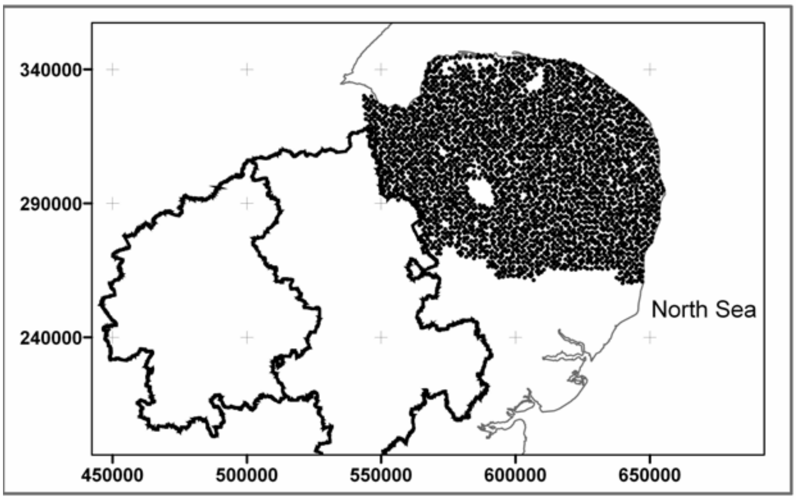

Figure 7 - Soil sampling locations from the G-BASE project for which analytical data are available in an area outwith the study region (proxy data) but in which some of the parent material types occur. The available data comprise As and Ni concentrations for topsoil (0-15 cm depth; black symbols). Coordinates are metres of the British National Grid.

3.5 STAGE 3 – LOWESTOFT AND LONDON CLAY FORMATIONS - LIKELIHOOD: CLASSIFICATION BASED ON PROXY AND PUBLISHED GEOCHEMICAL MAPS

Stages 1 and 2 provided likelihood classifications for parent material polygons covering the majority of the study region. Three parent material types that cover large areas in the south-east of the study region did not have any soil geochemical data from stage one of the study; the Lowestoft Formation Diamicton (BGS Lex-Rock code LOFT-DMTN), the Lowestoft Formation Sands and Gravels (LOFT-SAGR) and the London Clay Formation (LC-CLSS). Although proxy data were available for the two Quaternary Lowestoft Formation deposits, the greater heterogeneity of this material renders the use of data from outwith the study region problematic. We therefore chose to use two series of data to guide our classification of the Lowestoft Formation parent material types. First, by calculating the concentrations for these parent materials from the proxy soil geochemical data (stage 2). Second by using other substantive sources of geochemical information available for the south-east part of the study region; published versions of soil geochemical maps from the NSI (National Soil Inventory) for England and Wales (Oliver et al., 2001) and the stream sediment geochemical maps published in the Wolfson Atlas (Webb et al., 1978). In the case of the latter, although there are significant differences between soils and stream sediments in terms of their geomorphological derivation in the landscape, evidence from studies in the Humber-Trent region of the UK indicate that the latter do provide an indication of the likely geochemical content of the former (see Figure 2). In this region, the average concentration of arsenic in 6,500 soil samples was 16 mg/kg (Standard deviation=14 mg/kg), whilst the average for 4,200 stream sediments was 17.3 mg/kg (Standard deviation=18 mg/kg).

The proxy soil geochemical data for the Lowestoft Formation Diamicton (number of samples (n) = 1333) gave concentrations of 10.3 and 17.5 mg/kg for As and Ni respectively. In the case of the Lowestoft Formation Sands and Gravels, the soil concentrations (n=113) were 10.9 and 10.3 mg/kg for As and Ni respectively. We then used published versions of the Wolfson and NSI data to estimate Ni and As (in the former only) concentrations for stream sediments and soils over all three parent material types for which no data were available from Stages 1 and 2. The estimated values were all in the low likelihood category for As (<15 mg/kg) and Ni (<40 mg/kg). Given the fact that for the Humber-Trent region average As concentrations in the soil were below the average for stream sediments, we have more confidence in assigning the three parent material types in our study region to the lowest likelihood category for exceeding the As SGV (20 mg/kg). In summary, both the published version of the NSI and Wolfson atlases indicate that the As and Ni SGV's are unlikely to be exceeded in these areas.

3.6 PARENT MATERIAL TYPES FOR WHICH NO DATA ARE AVAILABLE

Within the study region there are 71 parent material types which generally cover small areas for which no geochemical data are available. In such circumstances, the parent material polygons are classified as 'no data' and shaded blue. If these areas are considered important in terms of development, it would be relatively inexpensive to establish the likelihood of the soil developed over such parent material types exceeding the SGV's for As and Ni by undertaking a limited amount of soil sampling and analysis. The most extensive parent material type for which no data are available are the Quaternary 'Clay-with-Flints' deposits that occur in the south-west of the study region, around Luton and towards Stevenage.

4 Areas and uncertainty in likelihood classes

Given the nature of the data available for the three stages outlined in the previous section, we have classified the study area according to the level of confidence we have in our predictions concerning likelihood of exceeding the SGV's for As and Ni (Table 2). A map showing these confidence levels across the study region is shown in Figure 8. This was derived from the GIS layer 'Confidence' in the companion product of this report. We have a high level of confidence in our prediction of the likelihood of exceeding the SGV's for As and Ni for around three-quarters of the total land area (Table 2).

Table 2 – Levels of confidence in predicting likelihood of exceeding the SGV's for As and Ni for the differing data availability across the study region

Level of confidence in prediction	Description of data availability	Land area (km ^{2})	Land area (%)	Map colour
High (Stage 1)	Soil geochemical data available from the G-BASE survey	8051	73	Dark blue
Moderate (Stage 2)	Proxy soil data available from the G-BASE survey	1937	18	Medium blue
Low (Stage 3)	Combination of proxy soil data for Quaternary parent materials and published Wolfson atlas based on stream sediment	452	4	Pale blue
No data	Small parent material polygons for which no data are available	546	5	Yellow

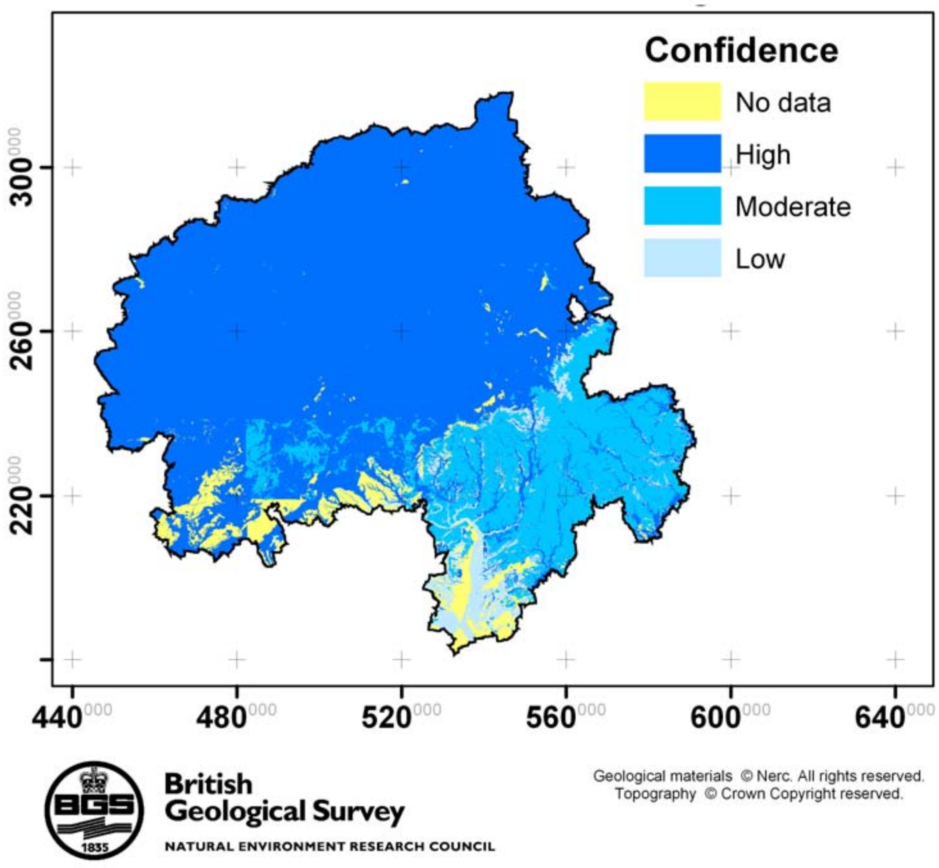

Figure 8 – Map showing the level of confidence in predicting likelihood of exceeding SGV's throughout the study region. Coordinates are metres of the British National Grid.

5 Likelihood map for arsenic

A map showing the likelihood of exceeding the As SGV is a product of the GIS associated with this report (Figure 9). Based on the areas of the individual parent material polygons, we calculated the total area for each of our three likelihood categories in relation to exceeding the As SGV (Table 3). For around half the total land area there is a moderate likelihood that the As SGV for residential land use will be exceeded. Perhaps more importantly, there are a series of parent material types generally in the north and west of the study region over which soils have a strong likelihood of exceeding the 20 mg/kg As SGV for residential land use. Considerable funding may be required in undertaking site-specific risk assessments in these areas prior to residential development. However, these elevated soil As concentrations should be confined to soils developed over specific bedrock lithologies, for which the available GIS layer provides a fine-resolution distribution (1:50,000 scale). If areas for which no data are available were considered important in terms of future development, it would be relatively inexpensive to establish the likelihood of the soil exceeding the SGV's for As by undertaking a limited amount of further soil sampling and analysis.

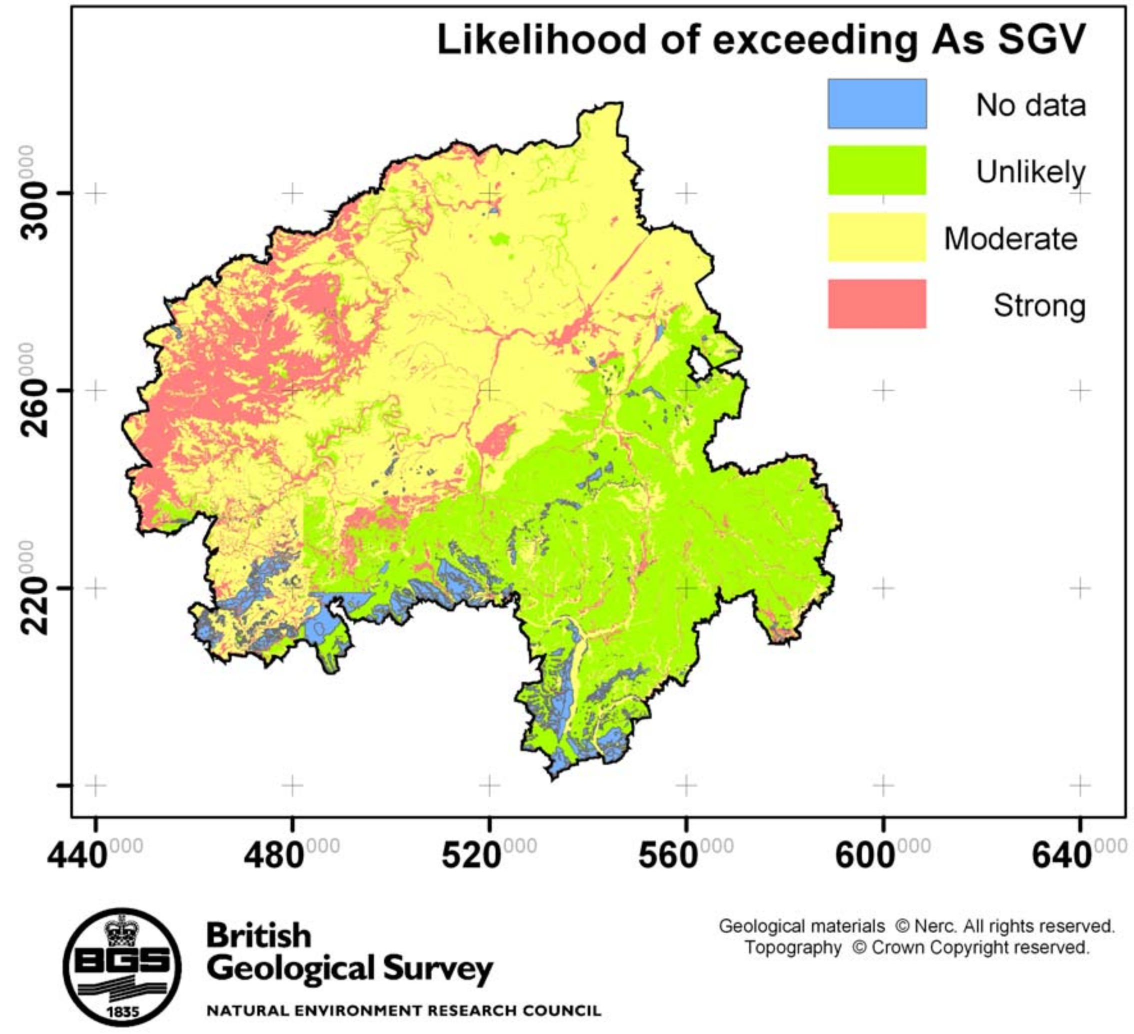

Figure 9– Map showing the likelihood of exceeding the residential SGV for As (arsenic) throughout the study region. Coordinates are metres of the British National Grid.

Table 3 – Likelihood of soil arsenic concentrations exceeding SGV (Table 1) throughout the study region and the total land area for each category

Likelihood category	Land area (km^2)	Land area (%)	Map colour
Unlikely	3501	32	Green
Moderate likelihood	5266	48	Yellow
Strong likelihood	1674	15	Red
No data	546	5	Blue

6 Likelihood map for nickel

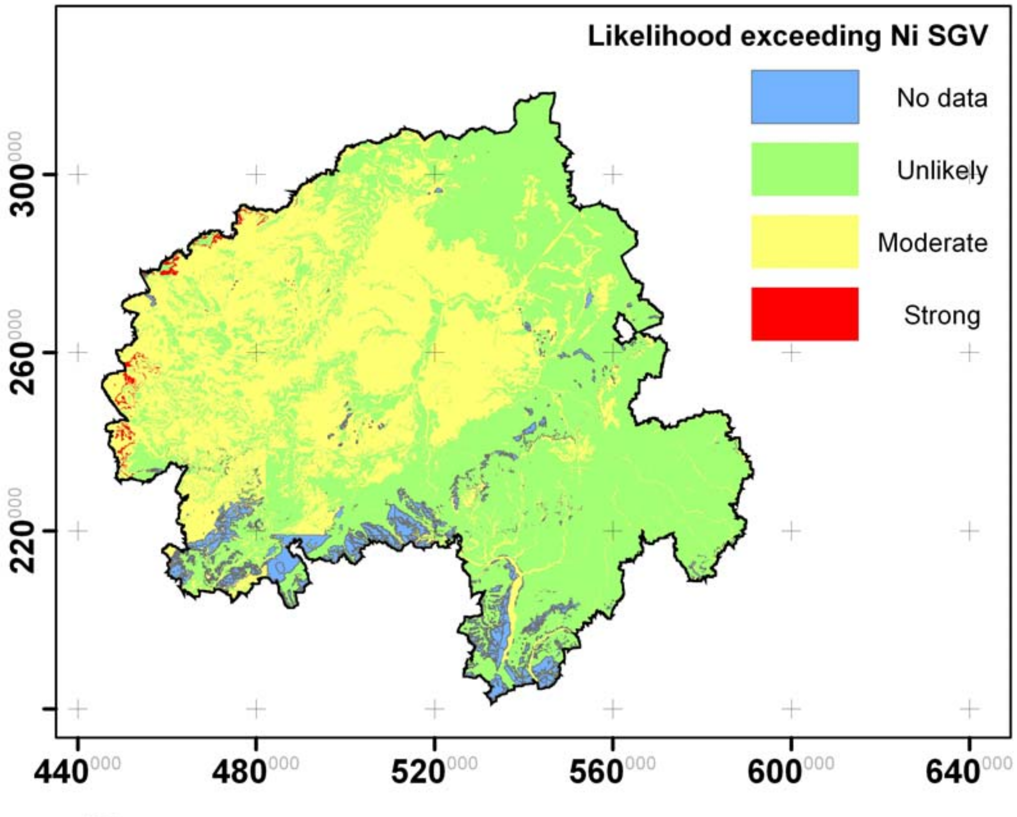

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Figure 10– Map showing the likelihood of exceeding the residential SGV for Ni (nickel) throughout the study region. Coordinates are metres of the British National Grid.

A map showing the likelihood of exceeding the Ni SGV is a product of the GIS associated with this report (Figure 10). Based on the areas of the individual parent material polygons, we calculated the total area for each of our three likelihood categories in relation to exceeding the Ni SGV (Table 4). For 40% the total land area, generally over the central and western areas of the study region, there is a moderate likelihood that the Ni SGV for residential land use will be exceeded. If areas for which no data are available were considered important in terms of future development, it would be relatively inexpensive to establish the likelihood of the soil exceeding the SGV's for Ni by undertaking a limited amount of further soil sampling and analysis.

Table 4 – Likelihood of soil nickel concentrations exceeding SGV (see Table 1) throughout the study region and the total land area for each category

Likelihood category	Land area (km^2)	Land area (%)	Map colour
Unlikely	5883	54	Green
Moderate likelihood	4520	41	Yellow
Strong likelihood	38	0.3	Red
No data	546	5	Blue

Appendix 1 Summary of the 154 parent material types in the study region

BGS Lex-Rock code	Parent material name	Parent material lithology description
ABSG-SAGR	ABBEY SAND AND GRAVEL	SAND AND GRAVEL
AGSP-SDST	ARNGROVE SPICULITE MEMBER	SANDSTONE
ALF-CSSG	ALLUVIAL FAN DEPOSITS	CLAY, SILT, SAND AND GRAVEL
ALF-SAGR	ALLUVIAL FAN DEPOSITS	SAND AND GRAVEL
ALF-SASI	ALLUVIAL FAN DEPOSITS	SAND AND SILT
ALV-CSSG	ALLUVIUM	CLAY, SILT, SAND AND GRAVEL
ALV-CZPS	ALLUVIUM	CLAY, SILTY, PEATY, SANDY
AMC-MDST	AMPTHILL CLAY FORMATION	MUDSTONE
BGS-SAND	BAGSHOT FORMATION	SAND
BHT-SAGR	BOYN HILL GRAVEL FORMATION	SAND AND GRAVEL
BLAD-LMST	BLADON MEMBER	LIMESTONE
BLAD-MDLM	BLADON MEMBER	MUDSTONE AND LIMESTONE, INTERBEDDED
BLCR-MDST	BLUE LIAS FORMATION AND CHARMOUTH MUDSTONE FORMATION	MUDSTONE
BPGR-SAGR	BLACK PARK GRAVEL FORMATION	SAND AND GRAVEL
BRK-CLSS	BRICKEARTH	CLAY, SILT AND SAND
BWC-MDST	BLISWORTH CLAY FORMATION	MUDSTONE
BWL-LMST	BLISWORTH LIMESTONE FORMATION	LIMESTONE
BYD-CLSI	BARROWAY DROVE BEDS	CLAY AND SILT
CB-LMST	CORNBRASH FORMATION	LIMESTONE
CHAM-LMST	CHARMOUTH MUDSTONE FORMATION	LIMESTONE
CHAM-MDST	CHARMOUTH MUDSTONE FORMATION	MUDSTONE
CKR-CHLK	CHALK ROCK MEMBER	CHALK
CLGB-CLSS	CLAYGATE MEMBER	CLAY, SILT AND SAND
CRAG-SAND	CRAG GROUP	SAND
CWF-CSSG	CLAY-WITH-FLINTS	CLAY, SILT, SAND AND GRAVEL
DHGR-SAGR	DOLLIS HILL GRAVEL FORMATION	SAND AND GRAVEL
DMG-SAGR	DUNSMORE GRAVEL	SAND AND GRAVEL
DYS-SIMD	DYRHAM FORMATION	SILTSTONE AND MUDSTONE, INTERBEDDED
ESI-CLSI	ENFIELD SILT FORMATION	CLAY AND SILT
FMB-LMST	FOREST MARBLE FORMATION	LIMESTONE
FMB-LSMD	FOREST MARBLE FORMATION	LIMESTONE AND MUDSTONE, INTERBEDDED
GDU-CLSS	GLACIAL DEPOSITS (UNDIFFERENTIATED)	CLAY, SILT AND SAND
GFDMP-SAGR	GLACIOFLUVIAL DEPOSITS (UNDIFFERENTIATED) (MIDDLE	SAND AND GRAVEL
GLLD-CLSS	GLACIOLACUSTRINE DEPOSITS (UNDIFFERENTIATED)	CLAY, SILT AND SAND
GLLMP-CLSI	GLACIOLACUSTRINE DEPOSITS (UNDIFFERENTIATED) (MIDDLE	CLAY AND SILT
GLLMP-CLSS	GLACIOLACUSTRINE DEPOSITS (UNDIFFERENTIATED) (MIDDLE	CLAY, SILT AND SAND
GLT-MDST	GAULT FORMATION	MUDSTONE
GOG-LMAR	GREAT OOLITE GROUP	LIMESTONE AND [SUBEQUAL/SUBORDINATE]
GRF-SDSM	GRANTHAM FORMATION	SANDSTONE, SILTSTONE AND MUDSTONE
GUGS-MDSS	GAULT FORMATION AND UPPER GREENSAND FORMATION	MUDSTONE, SILTSTONE AND SANDSTONE
HAGR-SAGR	HACKNEY GRAVEL FORMATION	SAND AND GRAVEL
HCK-CHLK	HOLYWELL NODULAR CHALK FORMATION	CHALK
HEAD1-CSSG	HEAD, 1	CLAY, SILT, SAND AND GRAVEL
HEAD-CLSI	HEAD (UNDIFFERENTIATED)	CLAY AND SILT
HEAD-CSSG	HEAD (UNDIFFERENTIATED)	CLAY, SILT, SAND AND GRAVEL
HEAD-GSSC	HEAD (UNDIFFERENTIATED)	GRAVEL, SAND, SILT AND CLAY
HISA-SAND	HILLMORTON SAND	SAND
HNCK-CHLK	HOLYWELL NODULAR CHALK FORMATION AND NEW PIT CHALK	CHALK
HYSA-SDST	HORSEHAY SAND FORMATION	SANDSTONE
IGLD-CLSI	INTERGLACIAL LACUSTRINE DEPOSITS	CLAY AND SILT
ILSI-CLSI	ILFORD SILT FORMATION	CLAY AND SILT
KC-MDST	KIMMERIDGE CLAY FORMATION	MUDSTONE

BGS Lex-Rock code	Parent material name	Parent material lithology description
KC-SISD	KIMMERIDGE CLAY FORMATION	SILTSTONE AND SANDSTONE
KES-SAGR	KESGRAVE FORMATION	SAND AND GRAVEL
KLB-SDSM	KELLAWAYS FORMATION	SANDSTONE, SILTSTONE AND MUDSTONE
KLC-MDST	KELLAWAYS CLAY MEMBER	MUDSTONE
KLOX-MDSS	KELLAWAYS FORMATION AND OXFORD CLAY FORMATION	MUDSTONE, SILTSTONE AND SANDSTONE
KLS-SDSL	KELLAWAYS SAND MEMBER	SANDSTONE AND SILTSTONE, INTERBEDDED
KPGR-CLSI	KEMPTON PARK GRAVEL FORMATION	CLAY AND SILT
KPGR-SAGR	KEMPTON PARK GRAVEL FORMATION	SAND AND GRAVEL
LASI-CLSI	LANGLEY SILT FORMATION	CLAY AND SILT
LCCK-CHLK	LEWES NODULAR CHALK FORMATION, SEAFORD CHALK FORMATION,	CHALK
LC-CLSS	LONDON CLAY FORMATION	CLAY, SILT AND SAND
LDE-CLSI	LACUSTRINE DEPOSITS (UNDIFFERENTIATED)	CLAY AND SILT
LDE-POCM	LACUSTRINE DEPOSITS (UNDIFFERENTIATED)	PEAT, ORGANIC MUD AND CALCAREOUS MUD
LESE-CHLK	LEWES NODULAR CHALK FORMATION AND SEAFORD CHALK	CHALK
LGS-SDST	LOWER GREENSAND GROUP	SANDSTONE
LHGR-SAGR	LYNCH HILL GRAVEL FORMATION	SAND AND GRAVEL
LI-SIMD	LIAS GROUP	SILTSTONE AND MUDSTONE, INTERBEDDED
LLL-LMST	LOWER LINCOLNSHIRE LIMESTONE MEMBER	LIMESTONE
LL-LMST	LINCOLNSHIRE LIMESTONE FORMATION	LIMESTONE
LMBE-CLSS	LAMBETH GROUP	CLAY, SILT AND SAND
LOFT-CLSI	LOWESTOFT FORMATION	CLAY AND SILT
LOFT-DMRC	LOWESTOFT FORMATION	DIAMICTON WITH CHALK RAFTS
LOFT-DMTN	LOWESTOFT FORMATION	DIAMICTON
LOFT-SAGR	LOWESTOFT FORMATION	SAND AND GRAVEL
LTH-SAGR	LETCHWORTH GRAVELS FORMATION	SAND AND GRAVEL
MRB-FGLS	MARLSTONE ROCK FORMATION	FERRUGINOUS LIMESTONE AND FERRUGINOUS
MRB-FLIR	MARLSTONE ROCK FORMATION	FERRUGINOUS LIMESTONE AND IRONSTONE
MRB-LMFE	MARLSTONE ROCK FORMATION	FERRUGINOUS LIMESTONE
MRB-OOLF	MARLSTONE ROCK FORMATION	OOIDAL IRONSTONE
MRCG-SAGR	MARCH GRAVEL	SAND AND GRAVEL
MR-CHLK	MELBOURN ROCK	CHALK
NPCH-CHLK	NEW PIT CHALK FORMATION	CHALK
NS-OOLF	NORTHAMPTON SAND FORMATION	OOIDAL IRONSTONE
NS-SDLI	NORTHAMPTON SAND FORMATION	SANDSTONE, LIMESTONE AND IRONSTONE
OXC-MDST	OXFORD CLAY FORMATION	MUDSTONE
PB-LMAR	PURBECK LIMESTONE GROUP	LIMESTONE AND [SUBEQUAL/SUBORDINATE]
PB-SDLM	PURBECK LIMESTONE GROUP	SANDSTONE AND [SUBEQUAL/SUBORDINATE]
PEAT-PEAT	PEAT	PEAT
PET-MDST	PETERBOROUGH MEMBER	MUDSTONE
PL-LMCS	PORTLAND GROUP	LIMESTONE AND CALCAREOUS SANDSTONE
POSA-CSDS	PORTLAND SAND FORMATION	CALCAREOUS SANDSTONE
POSA-LMCS	PORTLAND SAND FORMATION	LIMESTONE AND CALCAREOUS SANDSTONE
POST-LMST	PORTLAND STONE FORMATION	LIMESTONE
RLD-ARSL	RUTLAND FORMATION	ARGILLACEOUS ROCKS WITH SUBORDINATE
RLD-MDST	RUTLAND FORMATION	MUDSTONE
RLD-SIMD	RUTLAND FORMATION	SILTSTONE AND MUDSTONE, INTERBEDDED
ROSI-CLSI	RODING SILT FORMATION	CLAY AND SILT
RTD1-CLSI	RIVER TERRACE DEPOSITS, 1	CLAY AND SILT
RTD1-SAGR	RIVER TERRACE DEPOSITS, 1	SAND AND GRAVEL
RTD2-SAGR	RIVER TERRACE DEPOSITS, 2	SAND AND GRAVEL
RTD3-SAGR	RIVER TERRACE DEPOSITS, 3	SAND AND GRAVEL
RTD4-SAGR	RIVER TERRACE DEPOSITS, 4	SAND AND GRAVEL
RTD5-SAGR	RIVER TERRACE DEPOSITS, 5	SAND AND GRAVEL
RTDU-SAGR	RIVER TERRACE DEPOSITS (UNDIFFERENTIATED)	SAND AND GRAVEL
RXB-SAND	ROXHAM SAND MEMBER	SAND
SBY-MDST	STEWARTBY MEMBER	MUDSTONE
SGAO-SAGR	SAND AND GRAVEL OF UNCERTAIN AGE AND ORIGIN	SAND AND GRAVEL
SHHB-ARSL	SHARP'S HILL FORMATION	ARGILLACEOUS ROCKS WITH SUBORDINATE

BGS Lex-Rock code	Parent material name	Parent material lithology description
SLM-SHMD	SHELL MARL	SHELLY MUDSTONE
STAM-SDSL	STAMFORD MEMBER	SANDSTONE AND SILTSTONE, INTERBEDDED
STGR-SAGR	STANMORE GRAVEL FORMATION	SAND AND GRAVEL
SUPNM-UNKN	SUPERFICIAL DEPOSITS NOT MAPPED [FOR DIGITAL MAP USE ONLY]	UNKNOWN LITHOLOGY
T1T2-SAGR	RIVER TERRACE DEPOSITS, 1 TO 2	SAND AND GRAVEL
T2T3-SAGR	RIVER TERRACE DEPOSITS, 2 TO 3	SAND AND GRAVEL
T4T5-SAGR	RIVER TERRACE DEPOSITS, 4 TO 5	SAND AND GRAVEL
TAB-SAND	THANET SAND FORMATION	SAND
TALM-CLSS	THANET SAND FORMATION AND LAMBETH GROUP (UNDIFFERENTIATED)	CLAY, SILT AND SAND
TFD1-CLSI	TIDAL FLAT DEPOSITS, 1	CLAY AND SILT
TFD1-SASI	TIDAL FLAT DEPOSITS, 1	SAND AND SILT
TFD-CLSI	TIDAL FLAT DEPOSITS	CLAY AND SILT
TFD-SASI	TIDAL FLAT DEPOSITS	SAND AND SILT
TILMP-DMTN	TILL, MIDDLE PLEISTOCENE	DIAMICTON
TPGR-SAGR	TAPLOW GRAVEL FORMATION	SAND AND GRAVEL
TRD-CLSI	TIDAL RIVER OR CREEK DEPOSITS	CLAY AND SILT
TRK-CHLK	TOP ROCK [CONIACIAN]	CHALK
TTST-CHLK	TOTTERNHOE STONE MEMBER	CHALK
TUFA-CATU	TUFA	CALCAREOUS TUFA
TY-OOLM	TAYNTON LIMESTONE FORMATION	LIMESTONE, OOIDAL
UGS-SIMD	UPPER GREENSAND FORMATION	SILTSTONE AND MUDSTONE, INTERBEDDED
ULL-LMST	UPPER LINCOLNSHIRE LIMESTONE MEMBER	LIMESTONE
UPL-LMST	UPWARE LIMESTONE MEMBER	LIMESTONE
WBRO-LMST	WELLINGBOROUGH LIMESTONE MEMBER	LIMESTONE
WBRO-LSMD	WELLINGBOROUGH LIMESTONE MEMBER	LIMESTONE AND MUDSTONE, INTERBEDDED
WBS-FULL	WOBURN SANDS FORMATION	FULLERS EARTH
WBS-SDST	WOBURN SANDS FORMATION	SANDSTONE
WEY-MDST	WEYMOUTH MEMBER	MUDSTONE
WHL-LMST	WHITE LIMESTONE FORMATION	LIMESTONE
WHM-LMST	WHITBY MUDSTONE FORMATION	LIMESTONE
WHM-MDST	WHITBY MUDSTONE FORMATION	MUDSTONE
WHS-MDST	WHITCHURCH SAND FORMATION	MUDSTONE
WHS-SDST	WHITCHURCH SAND FORMATION	SANDSTONE
WMCH-CHLK	WEST MELBURY MARLY CHALK FORMATION	CHALK
WMCH-LMST	WEST MELBURY MARLY CHALK FORMATION	LIMESTONE
WOGR-SAGR	WOODFORD GRAVEL FORMATION	SAND AND GRAVEL
WTB-CLSI	WOODSTON BEDS	CLAY AND SILT
WWAC-MDST	WEST WALTON FORMATION AND AMPTHILL CLAY FORMATION	MUDSTONE
WWB-LMAR	WEST WALTON FORMATION	LIMESTONE AND [SUBEQUAL/SUBORDINATE]
WWB-MDSI	WEST WALTON FORMATION	MUDSTONE AND SILTSTONE
WWB-MDST	WEST WALTON FORMATION	MUDSTONE
WZCK-CHLK	WEST MELBURY CHALK FORMATION AND ZIG ZAG CHALK FORMATION	CHALK
ZZCH-CHLK	ZIG ZAG CHALK FORMATION	CHALK

Appendix 2 Summary arsenic and nickel soil geochemical data for parent material groups in the study region

PARENT MATERIAL NAME	Soil samples (n)	Average As	*Likelihood As	Average Ni	*Likelihood Ni
TILL. MIDDLE PLEISTOCENE	700	19	2	42	2
LOWESTOFT FORMATION	244	19	2	43	2
PEAT	225	20	2	34	1
OXFORD CLAY FORMATION	214	16	2	41	2
WHITBY MUDSTONE FORMATION	199	34	3	46	2
TIDAL FLAT DEPOSITS, 1	106	21	2	38	1
NORTHAMPTON SAND FORMATION	101	58	3	49	2
RIVER TERRACE DEPOSITS, 1	89	22	2	35	1
ALLUVIUM	87	29	3	49	2
TIDAL FLAT DEPOSITS	78	17	2	26	1
BLISWORTH LIMESTONE FORMATION	58	16	2	35	1
GLACIOFLUVIAL DEPOSITS (UNDIFFERENTIATED) (MIDDLE PLEISTOCENE)	57	26	3	40	1
RIVER TERRACE DEPOSITS, 1 TO 2	55	18	2	30	1
NORTHAMPTON SAND FORMATION	48	39	3	40	1
DYRHAM FORMATION	48	34	3	51	2
WOBURN SANDS FORMATION	45	52	3	45	2
GAULT FORMATION	44	13	1	50	2
CHARMOUTH MUDSTONE FORMATION	42	23	2	45	2
WEST WALTON FORMATION AND AMPTHILL CLAY FORMATION	41	21	2	40	2
KIMMERIDGE CLAY FORMATION	40	21	2	36	1
CORNBRASH FORMATION	37	19	2	42	2
BARROWAY DROVE BEDS	33	16	2	31	1
HEAD (UNDIFFERENTIATED)	31	20	2	34	1
LOWER LINCOLNSHIRE LIMESTONE MEMBER	31	18	2	35	1
RIVER TERRACE DEPOSITS, 2	30	18	2	35	1
WEST MELBURY MARLY CHALK FORMATION	29	7	1	28	1
RUTLAND FORMATION	25	14	1	29	1
LOWESTOFT FORMATION	24	24	2	37	1
GREAT OOLITE GROUP	23	15	1	37	1
BLISWORTH CLAY FORMATION	20	16	2	43	2
ZIG ZAG CHALK FORMATION	18	6	1	19	1
RUTLAND FORMATION	17	12	1	32	1
PETERBOROUGH MEMBER	17	18	2	47	2
AMPTHILL CLAY FORMATION	16	16	2	34	1
MARCH GRAVEL	16	19	2	27	1
TIDAL FLAT DEPOSITS, 1	15	14	1	29	1
MARLSTONE ROCK FORMATION	14	34	3	52	2
RIVER TERRACE DEPOSITS (UNDIFFERENTIATED)	14	20	2	34	1
STAMFORD MEMBER	13	41	3	35	1
KELLAWAYS FORMATION AND OXFORD CLAY FORMATION	13	17	2	35	1
RIVER TERRACE DEPOSITS, 3	11	16	2	29	1
HOLYWELL NODULAR CHALK FORMATION	10	6	1	16	1
WHITE LIMESTONE FORMATION	10	10	1	24	1
KELLAWAYS FORMATION	9	10	1	24	1
WELLINGBOROUGH LIMESTONE MEMBER	8	13	1	31	1
GRANTHAM FORMATION	8	38	3	37	1
TAYNTON LIMESTONE FORMATION	7	19	2	30	1

PARENT MATERIAL NAME	Soil samples (n)	Average As	*Likelihood As	Average Ni	*Likelihood Ni
BLUE LIAS FORMATION AND CHARMOUTH MUDSTONE FORMATION	7	22	2	64	3
MARLSTONE ROCK FORMATION	6	119	3	103	3
KELLAWAYS SAND MEMBER	6	15	2	29	1
NEW PIT CHALK FORMATION	6	0	1	5	1
HOLYWELL NODULAR CHALK FORMATION AND NEW PIT CHALK FORMATION	5	6	1	21	1
LACUSTRINE DEPOSITS (UNDIFFERENTIATED)	4	14	1	23	1
WELLINGBOROUGH LIMESTONE MEMBER	4	28	3	30	1
HORSEHAY SAND FORMATION	4	15	2	25	1
TIDAL RIVER OR CREEK DEPOSITS	4	17	2	29	1
KELLAWAYS CLAY MEMBER	3	17	2	32	1
UPPER LINCOLNSHIRE LIMESTONE MEMBER	3	16	2	41	2
SHARP'S HILL FORMATION	3	54	3	37	1
LACUSTRINE DEPOSITS (UNDIFFERENTIATED)	3	8	1	41	2
STEWARTBY MEMBER	2	17	2	47	2
TIDAL FLAT DEPOSITS	2	15	2	30	1
SHELL MARL	2	16	2	38	1
LETCHWORTH GRAVELS FORMATION	1	25	3	54	2
ALLUVIAL FAN DEPOSITS	1	24	2	45	2
ALLUVIAL FAN DEPOSITS	1	16	2	33	1
TUFA	1	69	3	57	2
CHARMOUTH MUDSTONE FORMATION	1	18	2	39	1
TOTTERNHOE STONE MEMBER	1	2	1	12	1
GLACIOLACUSTRINE DEPOSITS (UNDIFFERENTIATED) (MIDDLE PLEISTOCENE)	1	20	2	36	1
LINCOLNSHIRE LIMESTONE FORMATION	1	8	1	36	1
SAND AND GRAVEL OF UNCERTAIN AGE AND ORIGIN	1	18	2	29	1
LEWES NODULAR CHALK FORMATION AND SEAFORD CHALK FORMATION	1	23	2	70	2
GLACIOLACUSTRINE DEPOSITS (UNDIFFERENTIATED) (MIDDLE PLEISTOCENE)	1	18	2	20	1

* likelihood class descriptions are shown in Table 1

Appendix 3 Summary arsenic and nickel soil geochemical data for parent material groups based on soil ‘proxy’ samples outwith the study region

Parent material name	Proxy soil samples (n)	Avgerage As	Likelihood As	Average Ni	Likelihood Ni
BRICKEARTH	60	9.5	1	9.6	1
CRAG GROUP	31	8.5	1	6.4	1
HEAD (UNDIFFERENTIATED)	3	9.9	1	9.7	1
KESGRAVE FORMATION	3	7.6	1	9.6	1
LEWES NODULAR CHALK FORMATION	167	9.1	1	9.0	1
LOWESTOFT FORMATION	6	10.8	1	16.2	1
MELBOURN ROCK	2	8.4	1	13.8	1
WEST MELBURY CHALK AND ZIG ZAG CHALK FORMATION	39	11.1	1	14.7	1

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