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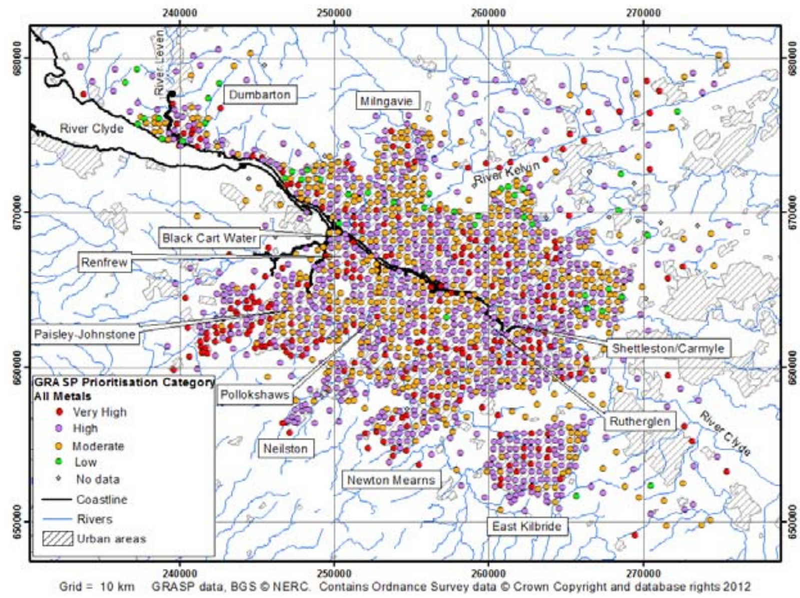
Developments to GRASP 2012/13. GRASP: a GIS tool to assess pollutant threats to shallow groundwater in the Glasgow area

Engineering Geology Programme

Internal Report IR/13/024



BRITISH GEOLOGICAL SURVEY

ENGINEERING GEOLOGY PROGRAMME

INTERNAL REPORT IR/13/024

Developments to GRASP 2012/13. GRASP: a GIS tool to assess pollutant threats to shallow groundwater in the Glasgow area

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GRASP prioritisation categories for Glasgow

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Contents

TABLES

FIGURES

1 Introduction

1.1 SUMMARY

The British Geological Survey (BGS) is developing a geographic information system (GIS)-based prioritisation tool known as GRASP (GRoundwater And Soil Pollutants). GRASP identifies and prioritises threats to shallow groundwater quality from the leaching and downward movement of metal pollutants in the soil and shallow sub-surface environment. Whilst developed for Glasgow, ultimately, its application should be wider. The GRASP tool is being developed as part of the Clyde and Glasgow Urban Super-Project (CUSP) and aims to aid urban planning and sustainable development by providing a broad-scale assessment of threats to groundwater quality across the Glasgow conurbation. This report describes the developments to GRASP in 2012 and 2013. It should be read in conjunction with the BGS internal reports IR/08/057 (Graham et al., 2008), IR/09/026 (Ó Dochartaigh et al., 2009) and IR/10/034 (Fordyce and Ó Dochartaigh, 2011), which describe in detail the initial creation and development of GRASP.

The following developments to GRASP were made in 2012/13:

- Refined GRASP methodology, to improve the way that soil leaching potential is combined with soil metal concentrations within the prioritisation tool

1.2 BACKGROUND

The GRASP GIS tool is based primarily upon an existing British Standard – International Standards Organisation (BS-ISO) methodology to assess the leaching potential of metals from soils, which has been validated for 11 metals: Al, Fe, Cd, Co, Cr, Cu, Hg, Ni, Mn, Pb and Zn (BS-ISO, 2004). Metal leaching potential is determined based on the following input parameters that control the leaching and migration of metals to groundwater:

Step 1: Soil Properties – Leaching Potential

Soil pH, organic carbon, clay and sesquioxide content – these parameters are fundamental to the soil's ability to bind and attenuate metals, making them unavailable for leaching

Step 2: Climatic Water Balance

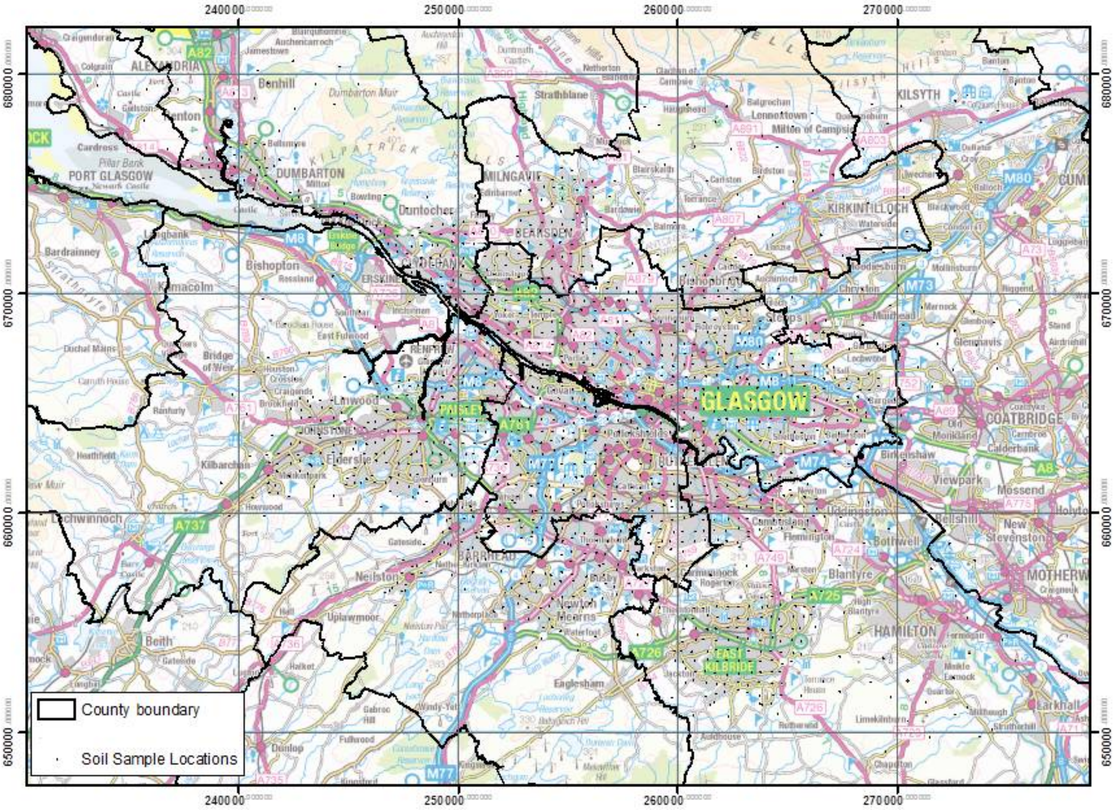
Effective rainfall infiltration – this parameter fundamentally controls the transport of metal pollutants through the soil

Step 3: Depth to Groundwater

Water level data – this parameter defines the length of travel of soil pollutants to the groundwater – the longer the travel time the greater the potential for metal attenuation

These input parameters, combined with additional information on the leaching potential of unsaturated Quaternary deposits, are used in the GRASP methodology to produce a series of leaching potential maps for each of the metals. GRASP is innovative in that it combines this information with actual data on the soil metal concentrations, to map out areas of the city where shallow groundwater quality is at greatest threat from the leaching and downward movement of metals in the soil. These maps are then combined into one overall prioritisation map for the city as the final output; this identifies the threat to shallow groundwater.

The soil property and metal content information used by the GRASP tool are based upon a systematic geochemical dataset of 1622 topsoils (0.05 – 0.20 m) and subsoils (0.35 – 0.50 m) collected across Glasgow as part of the BGS Geochemical Baseline Survey of the Environment (G-BASE) project (Fordyce et al., 2012). No G-BASE data are available for Hg. Therefore, it is not included in GRASP. Soil properties from the G-BASE dataset are combined with information on the nature of the underlying Quaternary deposits based on 1: 50,000-scale BGS DiGMapGB-50 data, to generate the soil leaching potential input parameters for the GRASP tool. Climatic data are derived from Meteorological Office (2013) datasets. Depth to groundwater information is taken from an existing BGS Scotland-wide model of groundwater levels in Glasgow, as real data values are not readily available on a city-wide basis. The extent of the GRASP study area is determined by the distribution of the G-BASE soil sample locations (Figure 1).



G-BASE data BGS, © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012

Figure 1. Location map of the GRASP study area based on G-BASE soil sample locations

The data processing for the GRASP methodology is carried out in a series of five steps in Microsoft Excel®, using Visual Basic® programming language, and in ArcGIS® software as outlined in Table 1.

Table 1. The five steps in the GRASP tool

GRASP Step	Description
Step 1	BS-ISO Step 1 Metal Binding Force Leaching Potential Assessment (Soil and Quaternary)
Step 2	BS-ISO Step 2 Climatic Water Balance Leaching Potential Assessment
Step 3	BS-ISO Step 3 Depth to Groundwater Leaching Potential Assessment
Step 4	Soil Metal Concentrations Threat Assessment
Step 5	Final Prioritisation Assessment

From Ó Dochartaigh et al. (2009)

Following the initial development of GRASP for Glasgow carried out in 2007 – 2008 (Graham et al., 2008); further adjustments to the method were made during 2008 – 2009 (Ó Dochartaigh et al., 2009) and 2009 – 2010 (Fordyce and Ó Dochartaigh, 2011). These included:

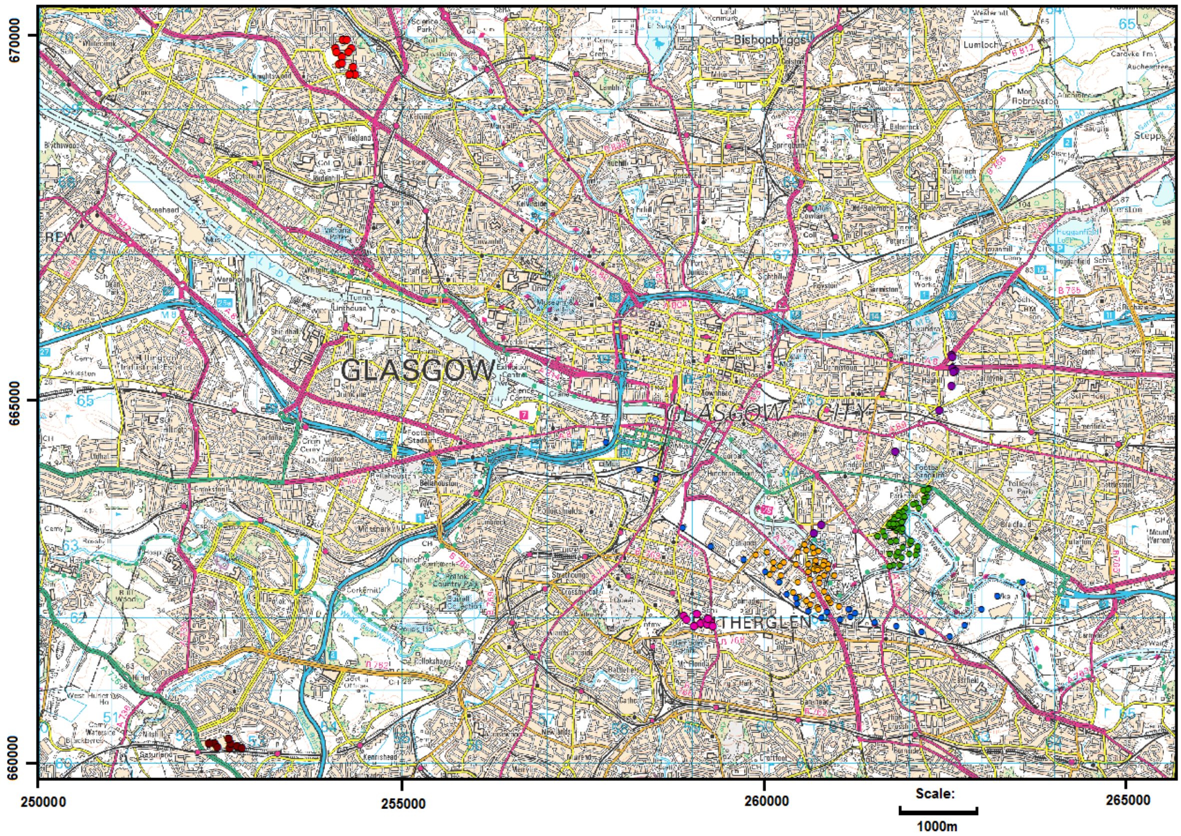
i. **Coding:** Modifications and improvements to the Visual Basic® code on which the GRASP tool is based.

ii. **Depth to Groundwater:** Investigations carried out within an MSc project with Strathclyde University (Lovatt, 2008), revealed that the GRASP tool was highly sensitive to the depth to water (DTW) input parameter. The DTW dataset initially used for GRASP was derived from a Scotland-wide model, rather than real data. This was only accurate to within approximately 3 m of real data, to the best of our current knowledge, based on available data for validation. Therefore, the MSc project aimed to collate a larger real dataset on DTW from existing site investigation and borehole records, held by Glasgow City Council (GCC) and BGS for a test area. However, the study revealed that there was very little detailed information on measured DTW levels in the existing records. High quality information was restricted to particular infrastructure corridors such as the M74, or recent active development sites. The results of the study indicated that collation of DTW levels from the extensive existing records for Glasgow was unlikely on its own to yield significantly better quality input data for the GRASP method. This makes the generation of a robust DTW map based on real values across the city difficult. Therefore, the GRASP tool still uses the DTW data from the Scotland-wide model, until such time as data from a dedicated groundwater monitoring network for Glasgow are available. A pilot network in part of Glasgow has been established, but measurements are required over a minimum two year period to build up a picture of DTW levels and there's not yet a network across the whole city (Ó Dochartaigh, 2009; Bonsor and Ó Dochartaigh, 2010). The limited data available for the initial validation of GRASP (Graham et al., 2008; Lovatt, 2008) revealed also that DTW was highly variable over very short distances, probably as a consequence of the extremely heterogeneous nature of the Quaternary deposits and made ground in Glasgow. It will be interesting to see whether the systematic data from the groundwater monitoring network show similar heterogeneity.

iii. **Quaternary Leaching Potential (QLP):** During 2008 – 2009, the method of incorporating the QLP was modified to utilise 1: 50,000-scale geological mapping information to categorise Quaternary deposits with a high clay (> 25%) and/or high organic carbon (> 1%) content as part of the subsoil characterisation carried out in Step 1 of GRASP.

iv. **Groundwater Chemistry Validation:** During 2009 – 2010, initial attempts were made to validate the GRASP outputs against groundwater chemistry data in Glasgow. However, investigations revealed very few existing representative groundwater quality data. The Clyde

Gateway was used as a small test area to validate GRASP as some information on Cr concentrations in groundwater was available from site investigation boreholes. The aim of the preliminary validation was to test whether high concentrations of Cr in groundwater were spatially coincident with areas highlighted by GRASP as being of high priority in terms of metals leaching from soil to groundwater. The Cr concentrations in groundwater were highly variable over short distances. Spatial comparisons revealed only a partial match of high Cr concentrations in groundwater and the GRASP very high priority locations (Fordyce and Ó Dochartaigh, 2011). A more comprehensive investigation to validate the GRASP outputs against groundwater chemistry data was carried out within an MSc project with Birmingham University (McCuaig, 2011). Groundwater chemistry data were retrieved from existing site investigation and borehole records collated by GCC and BGS as part of the Glasgow groundwater monitoring project (Bonsor et al., 2011). Data were available for seven study areas, mainly located in the East End of Glasgow (Figure 2). The results revealed that metal concentrations in Glasgow groundwater were high compared with baseline rural data (Ó Dochartaigh et al., 2011), reflecting urban pollution. The Glasgow groundwater chemistry data were categorised according to depth and likely Quaternary deposit unit. They were then compared (spatially and statistically) to the GRASP outputs and G-BASE soil chemistry dataset. The aim was to test whether high soil metal concentrations and/or high GRASP priority classes corresponded to areas of high groundwater metal concentration. The results revealed little relationship between the groundwater and soil chemistry datasets with the exception of Cr and Cu. In the case of Cr, this was due to the presence of Cr-waste from a former Cr-ore processing plant in the study area. Comparisons between Steps 3, 4 and 5 of the GRASP output and the groundwater chemistry data showed a statistically significant difference ($p=0.05$) for some elements between the low and high GRASP priority categories only. Factors such as complex Quaternary deposit geology, hydrogeology and groundwater flow paths and/or the presence of made ground and buried waste mean that groundwater chemistry in east-central Glasgow is highly variable, even between adjacent boreholes, making it difficult to predict at any given location. This in large part probably accounts for the limited association with the GRASP prioritisation categories. Although previous detailed site investigation studies have demonstrated an association between soil and groundwater chemistry in the area (Bewley, 2007), the G-BASE soil sampling 500 m grid on which GRASP is based, is generally not detailed enough to capture this level of variation. However, the highly variable groundwater chemistry results are also likely to reflect differing methods of data collection. For example, the collection of the samples from different depths and of mixed samples that average groundwater quality over the extent of a borehole, as well as different analytical techniques, detection limits and possible units of reporting errors between the sites. These discrepancies between the different datasets highlighted the difficulty in trying to use existing site investigation information to make comparisons between sites. Both these validation studies (Fordyce and Ó Dochartaigh, 2011; McCuaig, 2011) demonstrated the need for a systematic groundwater chemistry dataset for Glasgow.



Yellow: Shawfield, Blue: M74, Green: Commonwealth Games Village (CWGV), Purple: East End Regeneration Route (EERR), Pink: Myrtle Place, Red: Shafton Road, Brown: Cleeves Road.

Figure 2. Boreholes where groundwater chemistry data were available for GRASP validation (From: McCuaig, 2011).

v. **Soil Metal Concentrations:** During the original development of GRASP, the G-BASE soil metal chemistry information included in the prioritisation assessment was classified into low, moderate, high and very high hazard categories on the basis of percentiles of the data distribution. These classes reflected the inherently greater potential for metals at high concentration in the soil, to impact upon shallow groundwater quality. However, this did not equate to the concentrations in soils, at which leaching was likely to occur. During 2008 – 2009, these classes were examined further in relation to thresholds recommended by other organisations, such as the United States Soil Screening Levels (SSL) (US-EPA, 1996). On the basis of these studies, the 90th percentile soil metal concentration was taken as the upper class for GRASP as follows:

0 – 25th percentile = Low Metal Concentration Ranking

25 – 90th percentile = Moderate Metal Concentration Ranking

90 – 100th percentile = High Concentration Ranking

However, because of the way the soil leaching potential rankings were combined with the metal content rankings in Step 4 of the method, the high metal content class had no influence on the final high priority rankings. Therefore, further developments to the GRASP methodology were carried out during 2009 – 2010.

vi. **Updated Step 4:** In Step 4 of the GRASP methodology, the soil leaching potential rankings derived from Steps 1 – 3 are combined with the soil metal concentration rankings, to produce an overall prioritisation ranking of threats to shallow groundwater for each metal. In the

2009/10 version of GRASP, the matrix used to combine the soil metal concentrations and soil leaching potential was updated to give equal weighting to both sets of data (Table 2). Where both the soil leaching potential and the soil metal concentrations were high, a priority classification of very high was assigned, to reflect the greater likelihood of metals impacting on shallow groundwater quality at these locations.

Table 2. 2009/10 matrix defining how metal leaching potential rankings were combined with metal concentration categories

		G-BASE Metal Concentration Category (percentiles)		
		L (0 – 25)	**M (25 – 90)**	**H (90 – 100)**
GRASP Metal Leaching Potential Category (Step 3)	**H**	M	H	VH
	M	L	M	H
	L	L	L	M

This was done for both topsoil (A) and subsoil (S). The resultant outputs were threat prioritisation rankings for (i) topsoil and for (ii) subsoil for each metal. The prioritisation rankings for the topsoil (A) and subsoil (S) were then combined into a single ranking at each site, for each metal using a precautionary principle approach, whereby the highest prioritisation category for either the topsoil or subsoil was selected, according to the matrix shown in Table 3.

Table 3. Matrix illustrating the 2009/10 combination of topsoil and subsoil classes into a single ranking for each site, which was incorrect

		GRASP Topsoil (A Soil) Prioritisation Category from Step 4		
		L	**M**	**H**
GRASP Subsoil (S Soil) Prioritisation Category from Step 4	**H**	H	H	H
	M	M	M	H
	L	L	M	H

However, Table 3 did not take account of the very high class in Table 2, and this was an error in the method. Therefore, Step 4 has been revised further during 2012/13, as outlined in Chapter 2 of this report.

2 Revisions 2012/13 to GRASP Step 4

2.1 REVISED STEP 4

In Step 4 of the GRASP methodology, the soil leaching potential rankings derived from Steps 1 – 3 are combined with soil metal concentration rankings to produce an overall prioritisation ranking of threats to shallow groundwater for each metal. To correct the error in the previous version of the GRASP methodology, Step 4 has been revised to include the following stages. The revised version of the GRASP VBA code is outlined in Appendix 1 of this report.

Stage 1 Leaching Potential Categories from Step 3

This stage applies qualitative leaching potential values (low, moderate and high) to the numerical leaching rankings output from Step 3, according to the scheme outlined in Table 4. The categories are based upon the descriptions of the hazard ranks in the BS-ISO (2004) method. The categorised Step 3 output can be plotted as series of leaching potential maps; one for each of the ten metals, for which there are G-BASE soil data for Glasgow (Appendix 2).

Table 4. Qualitative Metal Leaching Potential categories in GRASP Steps 1 – 3.

GRASP Qualitative Soil Metal Leaching Potential Categories		
Low (BS-ISO hazard rank ≥ 0.0 < 2.5)	Moderate (BS-ISO hazard rank 2.5 – 3.5)	High (BS-ISO hazard rank > 3.5 ≤ 5.0)

From: Graham et al. (2008)

Stage 2 Calculation of Topsoil Metal Concentration Categories

This stage assigns qualitative hazard categories, based on metal concentrations in topsoil (A Soil). This scheme is based upon the premise that areas of higher soil metal concentrations pose an inherently greater risk to groundwater quality than areas of lower soil metal concentrations (Graham et al. 2008; Ó Dochartaigh et al., 2009 and Fordyce and Ó Dochartaigh, 2011).

In the previous versions of GRASP, the 90th percentile was selected as the basis for the upper hazard category, following comparisons with thresholds for soil metal threats to groundwater quality recommended by other organisations (US-EPA, 1996). These values are generic 'best estimates' of the concentrations at which attenuation capacity is likely to be exceeded in the soils, and metals are more likely to leach to groundwater. However, the lower hazard category was not amended to reflect these changes; it remained set at the lower quartile of the data distribution (25th percentile), as it had been during the initial phase of GRASP development (Graham et al., 2008). This has been redressed in the revised version of GRASP, such that the low metal concentration category is now set at half the higher category (i.e. 45th percentile) (Tables 5 and 6).

Table 5. Revised topsoil G-BASE metal concentration categories based on percentiles of the data distribution

Percentile	**Al_2O_3** wt%	**Cd** mg/kg	**Co** mg/kg	**Cr** mg/kg	**Cu** mg/kg	**Fe_2O_3** wt%	**MnO** wt%	**Ni** mg/kg	**Pb** mg/kg	**Zn** mg/kg	**Conc. Class**
0 – 45	14.4	0.25	24.0	104.0	45.0	6.29	0.099	43.1	108.9	135.1	Low
45 – 90	17.2	0.60	40.4	158.0	117.9	8.45	0.172	80.6	307.6	305.8	Moderate
90 – 100	25.6	16.00	560.0	4286.0	3679.9	20.18	0.878	1038.1	5001.0	1780.8	High

Stage 3 Calculation of Subsoil Metal Concentration Categories

This stage repeats Stage 2 for the subsoils (S Soils); namely it calculates qualitative hazard categories, based on metal concentrations in subsoil, according to the scheme outlined in Table 6.

Table 6. Revised subsoil G-BASE metal concentration categories based on percentiles of the data distribution

Percentile	**Al_2O_3** wt%	**Cd** mg/kg	**Co** mg/kg	**Cr** mg/kg	**Cu** mg/kg	**Fe_2O_3** wt%	**MnO** wt%	**Ni** mg/kg	**Pb** mg/kg	**Zn** mg/kg	**Conc. Class**
0 – 45	15.3	0.25	26.3	100.0	39.8	6.56	0.100	43.5	78.0	113.6	Low
45 – 90	18.8	0.50	49.9	150.0	123.4	8.97	0.185	88.9	301.1	292.6	Moderate
90 – 100	26.8	11.60	477.7	4363.0	3181.8	20.23	1.164	859.0	5001.0	1773.6	High

Stage 4 Combines Topsoil and Subsoil Metal Categories into One Soil Metal Concentration Category

This stage combines the metal concentration categories for topsoil (Soil A) and subsoil (Soil S), to produce a single metal concentration category for each metal for each soil site. This is done according to the matrix in Table 7. The matrix is devised to give a conservative estimate of threats from the soil metal concentration, based on a precautionary principle approach. The highest concentration class, in either topsoil or subsoil, is taken as the final metal concentration classification, for each metal for each soil site. The overall categorised output of this stage can be plotted as a series of metal concentration hazard maps, one for each metal (Appendix 3).

Table 7. Revised matrix defining how topsoil and subsoil metal concentration classes are combined to give one soil concentration class for each metal for each soil site.

		G-BASE Topsoil Metal Concentration Category (percentiles)		
		L (0 – 45)	**M (45 – 90)**	**H (90 – 100)**
G-BASE Subsoil Metal Concentration Category (percentiles)	**H (90 – 100)**	H	H	H
	M (45 – 90)	M	M	H
	L (0 – 45)	L	M	H

Stage 5 Combines Leaching Potential Category with Soil Metal Concentration Category

This stage combines the leaching potential hazard category, with the soil metal concentration category, to output a combined priority rank for each site for each metal. Again a precautionary principle approach is adopted, whereby the highest category of either the leaching potential class, or the soil metal class, is taken as the combined priority ranking, according to the matrix in Table 8. By definition, this generates many moderate and high ranks. Therefore, to highlight areas at greatest threat, where both the leaching potential and soil metal concentration categories are high, this is given a very high classification in the combined priority ranking.

Table 8. Revised matrix defining how leaching potential class from Step 3 and soil metal class from Stage 4 are combined to give a priority rank for each metal for each soil site.

		G-BASE Soil Metal Concentration Category		
		L	**M**	**H**
Step 3 Leaching Potential Category	**H**	H	H	VH
	M	M	M	H
	L	L	M	H

The output from Step 4 can be plotted as a set of individual prioritisation maps of threats to shallow groundwater; one for each metal across Glasgow (Appendix 4). The combined priority rankings for each metal at each soil location are output to Step 5.

2.2 STEP 5

As in the previous versions of GRASP, in Step 5 the ten individual priority metal rankings from Step 4 are collated into one overall prioritisation ranking. This step still uses the criterion from the previous version of GRASP, whereby the highest ranking for any metal at a soil site, determines the overall ranking; thus adopting the precautionary principle (Table 9).

Table 9. Criterion for combining the individual metal rankings from Step 4 into a single ranking in the current Step 5

Individual Metal Combined Priority Rankings from Step 4	Overall GRASP Priority Category in Step 5
All ten are low	Low
One or more is moderate; the rest are low	Moderate
One or more is high; the rest are low or moderate	High
One or more is very high, the rest low, moderate or high	Very High

From: Fordyce and Ó Dochartaigh (2011)

The revised outputs from the new GRASP method are discussed in Chapter 3 of this report.

3 Revised GRASP Outputs

3.1 STEP 3 LEACHING POTENTIAL

The outputs from Step 3 of GRASP have not changed in the revised version. Maps of the leaching potential hazard ranks for each metal at each soil location are shown in Appendix 2. As in the previous version of GRASP, the main control on the distribution of sites with low, moderate and high leaching potential is *depth to groundwater* (Figure 3), as the BS-ISO (2004) methodology is highly sensitive to this input parameter (Graham et al., 2008; Ó Dochartaigh et al., 2009). In particular, shallow depths to groundwater in the valleys of the Rivers Clyde, Kelvin, Leven and Black Cart Water have a significant control on the distribution of soil sites classed as high leaching potential for each metal (Appendix 2). However, it should be noted that there is uncertainty in the DTW input dataset used in the GRASP method, which is deemed to be accurate to within approximately 3 m only (See Section 1.2).

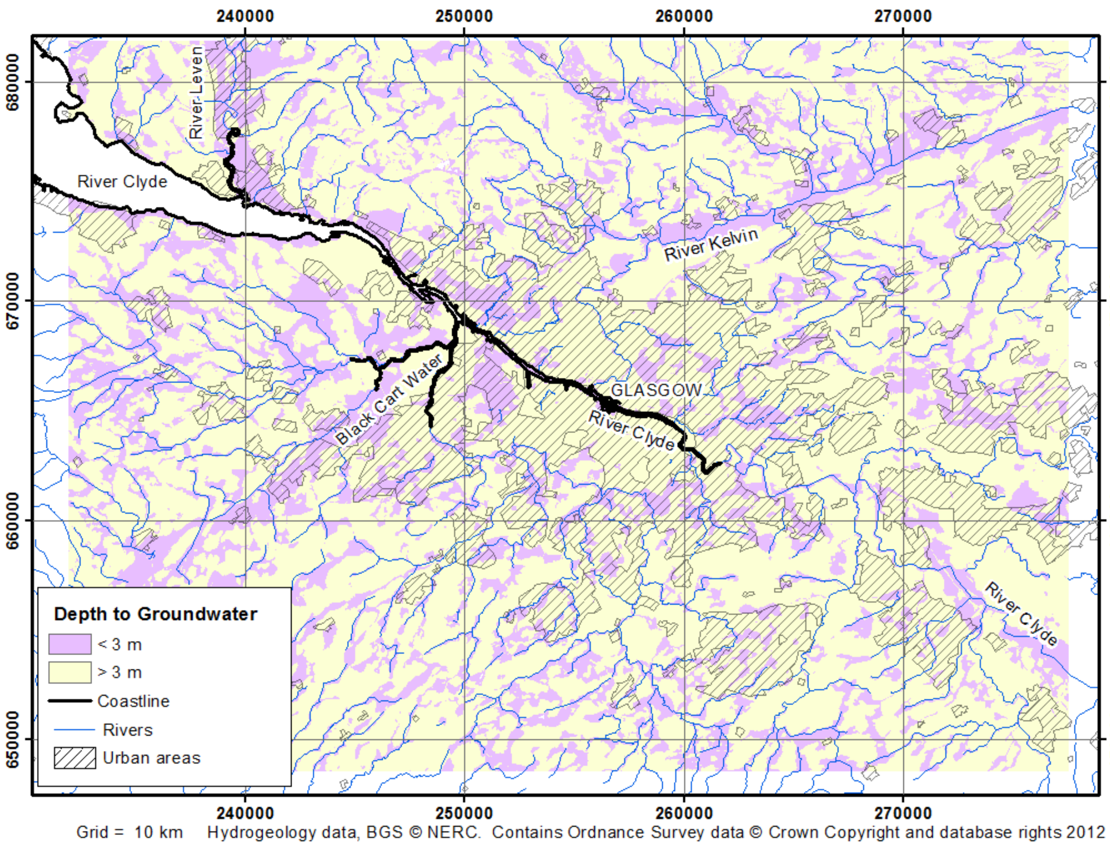


Figure 3. Map of predicted depth to groundwater level in the Glasgow area (BGS data)

3.2 STEP 4 SOIL METAL CONCENTRATION

In the revisions to the GRASP method, a new stage in Step 4 has been added to combine the topsoil and subsoil metal concentrations into one hazard rank output. In terms of soil metal rankings, at this stage of the GRASP process, with the exception of Cd, approximately 30% of the sites are classed as low; 50% of the sites as moderate and 15% as high soil metal concentration. Approximately 80% of the soils fall into the low soil metal class for Cd, because of the high proportion of values below the analytical detection limit (Table 10).

Table 10. Percentage of soil sites in each combined topsoil and subsoil metal concentration class from the current Step 4 of GRASP

Soil Metal Concentration Class	Al_2O_3	Fe_2O_3	MnO	Cd	Co %	Cr	Cu	Ni	Pb	Zn
Low	34	34	33	79	33	34	33	33	32	33
Moderate	52	52	52	6	52	51	52	52	53	53
High	14	14	15	14	15	15	15	15	15	15

Maps showing the soil metal concentration ranking for each metal, for each soil location, are presented in Appendix 3. The distribution of these hazard rankings can be explained by dividing the metals into three groups, as follows.

3.2.1 Al, Fe and Mn – Bedrock Geology Control

The first group comprises Al, Fe and Mn, which show a prevalence of low concentration ranked sites across north and north-west Glasgow. High ranked sites predominate on the southern periphery of the urban area, in the vicinity of Johnstone, Newton Mearns and East Kilbride. The distribution of these metals in soils is heavily influenced by the solid geology. Johnstone, Newton Mearns and East Kilbride are all underlain by lavas of the Clyde Plateau Volcanic Formation, which are naturally high in these metals (Fordyce et al., 2012).

3.2.2 Cd, Cu, Pb and Zn – Urban Control

The distribution of these metals is largely controlled by pollution from industrial and urban processes (Fordyce et al., 2012). Shipyards, heavy engineering, steel manufacturers, railway yards, gas works and other heavy industries, which are all sources of these metals in the environment, were all present across large areas of central and eastern Glasgow, the River Clyde corridor, Paisley and Johnstone during much of the 19th and 20th centuries; hence, the clusters of high values in these areas (Appendix 3). The distributions of these metals are also influenced by the traffic network, with higher concentrations in central Glasgow, and in the centre of East Kilbride (Appendix 3). By contrast, low concentrations are located in the rural environment around Glasgow; in the suburban periphery of East Kilbride, Newton Mearns, north Glasgow, Bearsden-Milngavie.

Cadmium is considered separately, as the metal concentration classes differ from those of the other metals (Appendix 3). This is due to the large proportion of soil Cd concentrations below the analytical detection limit. As a result, low concentration classes dominate the study area, with a cluster of high values in a small region centred on Shettleston, corresponding to the former industrial heartland of the East End of the city.

3.2.3 Co, Cr and Ni – Bedrock Geology and Urban Control

The distribution of the high concentration class for the third group of metals, comprising Co, Cr and Ni, shows features resembling both of the first two groups (Appendix 3). This reflects control by both the local geology and the presence of former industrial sites, on soil metal concentrations. On the one hand, concentrations are naturally high in areas underlain by the Clyde Plateau Volcanic Formation in Johnstone, Neilston and north-west East Kilbride. On the other hand, Cr and Ni concentrations in Johnstone are influenced also by the presence of made ground and urban pollution. Similarly, a marked cluster of high metal rankings is evident in the Rutherglen area, associated with the former metalworking heartland of the East End, including the world's largest chrome producing works, which was active during the 19th century (Fordyce et al., 2012). High soil concentrations of these metals are associated with the ship building corridor along the River Clyde also (Appendix 3).

3.3 STEP 4 COMBINED LEACHING POTENTIAL AND METAL CONCENTRATION PRIORITISATION OUTPUT

In the revised version of GRASP, the soil metal concentration ranks are combined with the leaching potential ranks from Step 3 to produce a combined priority rank. This highlights locations likely to be at greatest threat of leaching from soil to groundwater for each metal. Where both the leaching potential and soil metal concentration are high, a very high priority ranking is assigned.

The outputs from the new Step 4 methodology (Table 11) show that, with the exception of Cd, approximately 25% of the sites are classed as low combined priority. The majority of sites fall within either the moderate (approximately 40%) or high (approximately 33%) combined priority ranks for each metal. These results are a consequence of the precautionary principle approach, whereby the highest rank is selected from either the soil metal concentration or the leaching potential classes in Step 4. Due to the large number of soils with Cd concentrations below the analytical detection limit, 59% are classified as low combined priority, whereas only 5% are classed as moderate priority for this metal. The new method ranks approximately 5% of sites as very high combined priority, for each of the metals (Table 11). The way in which the very high combined priority class in the current version is calculated, better highlights the sites where the threat of soil pollutants leaching to shallow groundwater is most likely. As such, the GRASP method now more fully reflects the combination of known high soil metal concentrations in Glasgow, and the potential for metals to impact on shallow groundwater quality, which was the aim of developing the GRASP tool.

Table 11. Percentage of soil sites in each combined priority class for each metal from the current Step 4 of GRASP

Step 4 Prioritisation Class	Al_2O_3	Fe_2O_3	MnO	Cd	Co %	Cr	Cu	Ni	Pb	Zn
Low	25	25	24	59	23	23	23	26	24	22
Moderate	38	38	38	5	41	40	40	38	38	41
High	33	32	34	32	31	32	33	31	34	32
Very High	4	4	4	5	5	5	4	5	4	5

Maps showing the combined priority ranking for each metal for each soil location are presented in Appendix 4. Since the high leaching potential rank from Step 3 is predominately controlled by shallow depths to groundwater, in the combined priority maps, several of the very high ranked areas are focussed in the valleys of the Rivers Kelvin, Leven, Black Cart Water and Clyde as follows. Several soil sites are categorised as very high priority in the valley of the River Kelvin to the north of Glasgow for Al, Fe, and Mn and, to a lesser extent, Cd, Co, Cr and Ni, reflecting both shallow groundwater depths and naturally higher concentrations of these metals (Appendix 4). Very high priority classes in the Dumbarton area are a result of shallow groundwater depths in the valley of the River Leven, as well as urban soil pollution and presence of made ground for Cd, Co, Cr, Cu, Ni, Pb and Zn (Appendix 4). Similarly, very high categories in the ship building corridor of the River Clyde and in the East End of Glasgow, for Cd, Co, Cr, Cu, Ni, Pb and Zn reflect shallow groundwater depths and high soil metal concentrations, associated with current and former heavy industry and made ground in these locations (Fordyce et al., 2012). The clusters of very high priority rank in the Johnstone area, for Al, Cd, Co, Cr, Fe, Ni and to a lesser extent Cu, Mn, Pb and Zn, are indicative of shallow depths to groundwater in the Black Cart Water catchment, as well as a combination of naturally higher concentrations of Al, Co, Cr, Fe, Mn, and Ni associated with the Clyde Plateau Volcanic Formation, urban pollution and made ground (Cd, Cu, Cr, Ni, Pb and Zn). The small clusters of very high priority sites, on the southern fringes of Glasgow around Neilston (Fe, Mn and to a lesser extent Cr and Ni), Newton Mearns (Fe, Mn and to a lesser extent Ni) and East Kilbride (Al, Fe and Mn), are controlled by the higher concentrations of these metals in soils underlain by the Clyde Plateau Volcanic Formation and concordant shallow groundwater locations. Small clusters of very high values (Cd, Co, Cr, Cu, Ni, Pb and Zn), to the north of the city centre and an east–west band across southern Glasgow in the Carmyle–Pollokshaws area, are controlled by shallow groundwater depths, where these coincide with high soil metal concentrations in these urban environments (Appendix 4).

3.4 REVISED STEP 5 OUTPUT

In the final step of the GRASP tool, the ten individual metal combined priority rankings from Step 4 are collated into one overall prioritisation ranking for all metals (Step 5) (Table 12).

In the revised version of GRASP, 3% of the sites are categorised as low overall priority; 33% as moderate priority and 50% the sites as high overall priority (Table 12). Again this is a consequence of the precautionary approach, whereby the higher rank of any individual metal combined priority class is taken in the overall assessment. In the new version, 15% of the sites are classed very high overall priority.

Table 12. Percentage of soil sites in each prioritisation rank for all metals from the current Step 5 of GRASP

Prioritisation Rank	All Metals %
Low	3
Moderate	33
High	50
Very High	15

A map of the new final GRASP prioritisation rankings is presented in Figure 4. A major control on the distribution of very high priority sites is shallow groundwater depths, in a band across the south of the city (Carmyle–Pollokshaws); in the valleys of the River Clyde, the River Kelvin, the River Leven at Dumbarton and the Black Cart Water in the Paisley–Johnstone–Renfrew areas of the city.

Shallow groundwater depths also influence the very high priority rankings to the north of the city centre, on the southern fringes of Glasgow, in the East End of Glasgow, as well as in East Kilbride. However, it should be noted that there is uncertainty in the modelled DTW dataset used in the GRASP method, which is only accurate to within approximately 3 m of real observations (See Section 1.2). The distribution of very high priority sites also reflects high soil metal concentrations at these locations. As outlined in Section 3.3 of this report these may be natural (e.g. East Kilbride and the southern edge of the city); or associated with former industrial areas (e.g. Paisley–Renfrew, East End–Rutherglen and the River Clyde corridor) or with made ground and urban pollution, such as in Dumbarton and sporadic locations to the north and south of the city centre.

The very high rank in the revised version of GRASP focuses attention on sites where metals in soil are most likely to migrate to shallow groundwater; reflecting both locations where soil metal concentrations are known to be high and where leaching potential is also high. The aim is to prioritise these areas for attention in terms of groundwater protection.

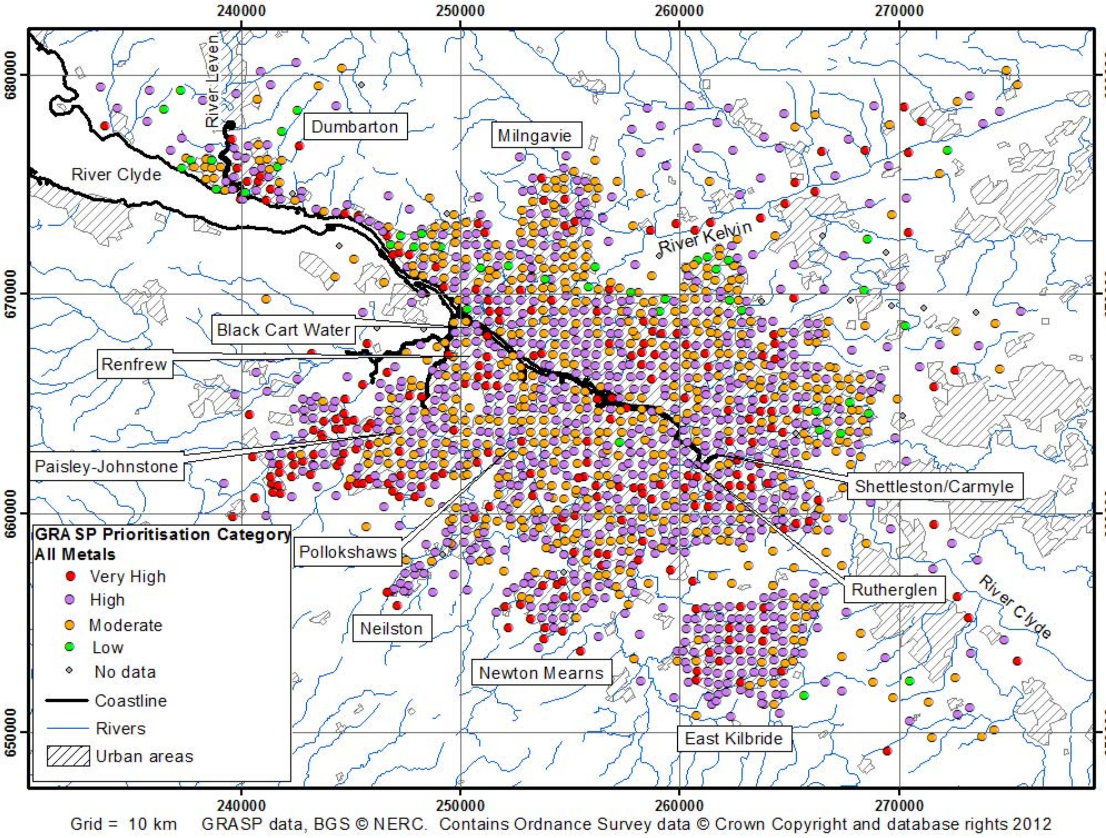


Figure 4. Overall leaching threat prioritisation rankings for the Glasgow area from the current version of GRASP

3.5 VALIDATION OF GRASP

The revisions to the GRASP method carried out during 2012 and 2013 resulted in very minor changes to the pattern of low, moderate, high and very high priority sites across the city. Therefore, previous studies to validate the GRASP prioritisation outputs against groundwater chemistry data are pertinent to the current version of GRASP. As outlined in Section 1.2 of this report, validation of the GRASP method has focussed on the East End of Glasgow, as this is where much recent development has taken place; hence, groundwater chemistry data from existing site investigation reports are available (Fordyce and Ó Dochartaigh, 2011; McCuaig, 2011). However, this area was the industrial heart of the city and as such, is very much affected by the presence of buried industrial waste, made ground and land pollution. The validation studies indicate that groundwater chemistry is very variable over short distances in this area. This is probably due in part to the highly heterogeneous nature of the Quaternary and made ground deposits, and resultant complexity of the hydrogeological regime in the East End of Glasgow. In addition, the different methods of collection and analysis used by various site investigations also lead to inconsistencies in groundwater chemistry data between adjacent boreholes, making comparisons between sites difficult (Fordyce and Ó Dochartaigh, 2011; McCuaig, 2011). What is not clear is whether other parts of the city, such as residential areas that have remained relatively undisturbed for decades, show similar variability, as there are no groundwater chemistry data in these areas. Therefore, there is a need for a systematic groundwater chemistry dataset for Glasgow. Until such time as more data become available, it is not possible to validate the GRASP method further.

The initial studies to validate GRASP indicate limited spatial relationships between the GRASP high priority outputs and areas of elevated metal concentration in groundwater. This is in part due to the inconsistencies in groundwater chemistry information between the different site investigation datasets, but is likely to reflect also the highly variable nature of the hydrogeological regime in the East End of Glasgow (Fordyce and Ó Dochartaigh, 2011; McCuaig, 2011). Although previous detailed site investigation studies have demonstrated an association between soil and groundwater chemistry in the area (Bewley, 2007), the G-BASE soil sampling 500 m grid on which GRASP is based, is generally not detailed enough to capture this level of variability. Therefore, trying to base a threat to groundwater tool on the G-BASE dataset in this area has been of limited success. The GRASP method may work better in areas with less complex made ground and Quaternary deposits. Glasgow is probably fairly typical of many cities with a long industrial heritage, in that a history of made ground/waste disposal adds to the complexity of the sub-surface environment, making it difficult to predict groundwater quality on a wider scale than site-specific investigation.

As outlined in Chapter 3 of this report, the prioritisation outputs from the GRASP method are heavily influenced by the DTW input parameter. Due to a lack of real DTW data for Glasgow, this parameter is currently derived from a Scotland-wide model, and is only accurate to within approximately 3 m of real data (Graham et al., 2008). New information on groundwater levels in part of Glasgow is currently being generated by a groundwater monitoring network, recently developed by the BGS and GCC (Bonsor et al., 2011). Once available, this new information should help validate the DTW model for Glasgow, improving the accuracy of this input parameter in the GRASP method.

4 Conclusions and Future Recommendations

General:

1. GRASP is a GIS-based prioritisation tool. It assesses relative threats to shallow groundwater quality from soil pollutants in the Glasgow area, using datasets of soil properties, total soil metal concentrations, Quaternary deposit properties, climate, and depth to groundwater.
2. GRASP is based on a methodology described by BS-ISO (2004), which assesses the potential for 11 metals (Al, Fe, Cd, Co, Cr, Cu, Hg, Ni, Mn, Pb and Zn) leaching from unsaturated soils to impact upon groundwater quality. It was developed further, by including data on the clay and organic carbon content of unsaturated Quaternary deposits, and on the total concentrations of ten of these metals (not including Hg) in the soils. The output is a set of prioritisation maps, which show the relative threat to shallow groundwater quality, for each of these metals leaching from the soil. In the final stage, the individual metal prioritisation categories are combined into a single category representing the overall threat to shallow groundwater quality from soil metal leaching.
3. GRASP is a method of highlighting threats to shallow groundwater quality; therefore of prioritising the need for site investigations to examine land quality. It is not a deterministic tool for measuring absolute levels of groundwater metal pollution, resulting from metals in soils.
4. During 2012–2013, developments to the GRASP methodology focussed on the following area:
   (i) Refine the GRASP methodology to correct errors in the way that soil leaching potential is combined with soil metal concentrations within Step 4 of the prioritisation tool

Refinements to Step 4 of GRASP:

5. Step 4 of the GRASP methodology combines soil/Quaternary deposit leaching potential hazard rankings derived from Steps 1–3, with hazard rankings of known soil metal concentrations from the G-BASE geochemistry database for Glasgow. In the first stage, qualitative hazard ranks (low, moderate and high), are assigned to the leaching potential output from Step 3. In the next two stages, metal concentrations in topsoil and then subsoil are categorised as low, moderate or high hazard ranks according to percentiles of the data distribution. In the next stage, the topsoil and subsoil metal concentrations are combined into one soil metal concentration ranking scheme. In the last stage, these are combined with the leaching potential rankings from Step 3, to produce a combined priority ranking for each of the ten metals, as the final output of Step 4. Locations where both soil metal concentration and soil leaching potential are high are highlighted as very high priority in the new Step 4 output. This reflects the greater likelihood of metals impacting on shallow groundwater quality at these locations.
6. The result of this revised method is that at the end of Step 4, for each of the ten metals, 5% of soil sample sites are classified as very high priority.
7. The results for each of the ten metals are then combined into one overall prioritisation ranking in Step 5 of the GRASP method. As a result of the revisions to Step 4, in the overall final output, 15% of the sites are now classed as very high priority.

8. The way the soil metal content data and the leaching potential data are combined in GRASP means that the very high class now better highlights the sites where the threat of soil pollutants leaching to shallow groundwater is most likely.
9. The main controls on the very high priority classification are (i) the depth to groundwater input parameter (which has a major influence on the leaching potential rank in Step 3) and (ii) high soil metal concentrations.
10. The final output from GRASP highlights areas of very high priority across the city; these are significantly controlled by shallow groundwater depths. They include a band across the south of the city (Carmyle–Pollokshaws) and the valleys of the River Clyde, the River Kelvin, the Black Cart Water and the River Leven at Dumbarton. Shallow groundwater depths influence the very high overall priority rankings in East Kilbride and in the East End of Glasgow also. However, the distribution of very high priority sites also reflects high soil metal concentrations at these locations. These may be natural (as in the case of East Kilbride and the southern edge of the city), or may be associated with former industrial areas (such as Johnstone, East End–Rutherglen and the River Clyde corridor) or with made ground and urban pollution such as in Dumbarton and sporadic locations to the north of the city centre.

Future Recommendations:

11. Although the GRASP method now better combines known soil metal concentrations with leaching potential estimates to produce a priority assessment of threats to shallow groundwater quality; it is not known if the method is valid, as it has yet to be fully tested against real groundwater chemistry data. This is because there is currently a lack of groundwater chemistry data for Glasgow. To date, validation of the GRASP method has focussed on development areas in the East End of Glasgow as this is where groundwater chemistry data from existing site investigation reports are available. The initial studies to validate GRASP show limited spatial relationships between the GRASP high priority sites and areas of elevated metal concentration in groundwater or between soil and groundwater chemistry. Factors such as complex Quaternary deposit geology, hydrogeology and groundwater flow paths and/or the presence of made ground and buried waste mean that groundwater chemistry in east-central Glasgow is highly variable, even between adjacent boreholes, making it difficult to predict at any given location. This in large part probably accounts for the limited association with the GRASP prioritisation categories. The G-BASE soil sampling 500 m grid, on which GRASP is based is generally not detailed enough to capture this level of variation. Therefore, trying to base a threat to groundwater tool on the G-BASE dataset may be successful only in areas with less complex geological and anthropogenic sequences. **It is recommended that** the GRASP method is tested in an urban environment with simpler made ground and Quaternary deposits.
12. Attempts to validate the GRASP method have underlined the lack of groundwater chemistry data available for Glasgow. Data are available from existing site investigation reports in development areas only. Evidence from this study suggests that part of the variability in the groundwater chemistry data for Glasgow is a result of the different methods of data collection and analysis used by various site investigations. This leads to inconsistencies in groundwater chemistry data between adjacent boreholes, making comparisons between sites difficult. These issues highlight the need for a systematic groundwater chemistry dataset for Glasgow. **It is recommended** that should more data become available in the future, these are used to validate the GRASP method.
13. Studies to validate the GRASP model indicate that it is highly sensitive to the depth to water (DTW) input parameter. This parameter has a very significant bearing on the prioritisation outputs from the GRASP method also. This parameter is currently based on a Scotland-wide model that is accurate to within approximately 3 m only, as there is a lack of real DTW data

for Glasgow. However, a groundwater monitoring network has been established recently in part of Glasgow. **It is recommended that** new information from this network is used to validate the DTW model and improve the robustness of this input parameter in the GRASP method in the future.

Glossary

BGS	British Geological Survey
BS-ISO	British Standards – International Standards Organisation
CUSP	Clyde and Glasgow Urban Super-Project
CWGV	Commonwealth Games Village
DTW	Depth to Water
EERR	East End Regeneration Route
G-BASE	Geochemical Baseline Survey of the Environment
GCC	Glasgow City Council
GIS	Geographic Information System
GRASP	GRoundwater And Soil Pollutants
SSL	Soil Screening Level
QLP	Quaternary Leaching Potential
US-EPA	United States Environmental Protection Agency

References

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Appendix 1 Revised Step 4 GRASP VBA Code

The latest version of the GRASP VBA code is held in the following BGS corporate data folder:
W:\Teams\RSS\Clyde_Basin\Data\Hydrogeology\Data\GRASP\VBA\GRASPcode_Aug2013

The revised version of the code created during 2013 is as follows:

```
Sub Step4()
'*****************************************************************************
'This routine is the main calling routine for STEP 4 of GRASP.
'Step 4 determines the Soil Metal Concentrations Threat.  There are 3 main stages to
'this assessment.
'1) The leaching potential output from STEP 3 is converted to a qualitative threat
   'H, M, or L.  The ranked Step 3 output is printed to worksheet "Step3_rank".
'2) The soil metal concentrations threat is then assessed, based on the recorded metal
   'concentrations within the soil. This is done for both A Soils and S Soils.
'3) The output for the A and S soil horizons are compared and the highest threat
   'category is output.
'4) A combined threat priority rank value is applied, based on the metal concentration threat
   'and the leaching potential threat.  This final combined hazard value is output to Step 5.
'*****************************************************************************
Dim i As Integer
Dim j As Integer
Dim k As Integer
Dim mcol As Integer
Dim mrow As Integer

'Interrogate data for each of 1622 sites one by one - i is the row number in the data
'worksheets. There are 1623 rows (sites) for A soils; fewer for S soils but there are
'blank rows in the "Step5_OutputS" worksheet to allow for this
For i = 2 To 1623
'Search through columns of worksheets. These are columns 6 to 15 in "A_Soils" and
'"S_Soils"
   For j = 6 To 15

'Convert the leaching potential output from STEP 3 is converted to a qualitative threat
'H, M, or L.  The ranked Step 3 output is printed to worksheet "Step3_rank".
      Call S3rank(i, j)

'Calculate the soil metal concentrations threat in the A and S soil horizons, based
'on the recorded metal concentrations within the soil. The calculated threat is
'output to worksheets "Step4_outputA" and "Step4_outputS".
      Call RiskCalc(i, j, mcol, mrow, k)

Next j
Next i

'Compare the soil metal concentrations threat calculated for the A and S soil horizons
'and output the highest threat category to worksheet "Step4_OverallOutput".
'This is the final output from Step 4 GRASP.
```

```
'Read through data for all 1622 sites one by one
For i = 2 To 1623
'Search through all the columns of calculated threat output for the A and S soil
'horizons.
 For j = 4 To 13

'Compare threat output for A and S soil horizons. Output highest threat category.
'If missing data for one of the soil horizon, the "nodata" error warning is output
'and not the threat calculated from just one soil horizon.
      Call OverallRisk(i, j)

'Compare the final combined output threat category, based on the soil concentrations, with
'the leaching potential threat calculated in Step 3.
'This gives an output of Combined threat priority Class, and is the final output of Step 4.
      Call CombinedClass(i, j)

'* Output Step 4 results of 'Combined Priority Risk' to workbook "Step 5" for use in subsequent
'stages of GRASP model
Workbooks("Step5.xls").Worksheets("Step4_CombinedPriorityClass").Cells(i, j) =
Worksheets("Step4_CombinedPriorityClass").Cells(i, j)

Next j
Next i
End Sub
Sub S3rank(i, j)
'*****************************************************************************
'This subroutine converts the leaching potential output from STEP 3 to a qualitative threat,
'H, M, or L.  This ranked Step 3 output is printed to worksheet "Step3_rank".
'*****************************************************************************
'Read data values in "Step3_output" and convert to a numerical rank, H, M or L
      If Worksheets("Step3_output").Cells(i, j) <= 2.5 Then
         Worksheets("Step3_rank").Cells(i, j) = "L"
      End If
      If Worksheets("Step3_output").Cells(i, j) > 2.5 And Worksheets("Step3_output").Cells(i, j)
<= 3.5 Then
         Worksheets("Step3_rank").Cells(i, j) = "M"
      End If
      If Worksheets("Step3_output").Cells(i, j) > 3.5 Then
         Worksheets("Step3_rank").Cells(i, j) = "H"
      End If

'* If data values in "Step3_output" are data error warnings, these warnings must be output to
'* worksheet "Step3_rank" instead of a rank value
      If Worksheets("Step3_output").Cells(i, j) = "noCWB" Then
         Worksheets("Step3_rank").Cells(i, j) = "noCWB"
      End If
      If Worksheets("Step3_output").Cells(i, j) = "noDTW" Then
         Worksheets("Step3_rank").Cells(i, j) = "noDTW"
      End If
      If Worksheets("Step3_output").Cells(i, j) = "na" Then
         Worksheets("Step3_rank").Cells(i, j) = "na"
      End If
End Sub
```

```
Sub RiskCalc(i, j, mcol, mrow, k)
'*****************************************************************************
'This subroutine calculates the soil metal concentrations threat, for both A and S soil
'horizons, based on the recorded metal concentrations within the soil.
'*****************************************************************************

'Search through columns of worksheets. These are columns 6 to 15 in "A_Soils" and "S_Soils",
'but are columns 2 to 11 in "PercentileA" and "PercentileS" (hence j-4 is used) and columns 4 to
13 in
'"OutputA", "OutputS" and "S4"(hence j-2 is used).
If IsNull(Worksheets("A_Soils").Cells(i, j)) Then
   mcol = 7
   mrow = 6
   MsgBox (Worksheets("A_Soils").Cells(i, j))
   Else

'The code then:
'Determines the correct percentile bin, according to the metal concentration 'and assigns correct
column of matrix.
'Outputs the rank value from this column in the matrix to the worksheets "OutputA" and
"OutputS"

'The five values of k represent the five percentile bins
      For k = 1 To 5
'Check whether the concentration for a given site (i) and element (j) is less than or
'equal to the maximum concentration in a given percentile class.  This condition may be
'satisfied for several values of k (e.g. a concentration in the 45–90th percentile class
'will be less than both the 100th and 90th percentile values), giving different values
'of mcol.  Using (7-k) to refer to the rows in "PercentileA" and "PercentileS" means that the
lowest 'percentile class satisfying this criterion is encountered last, meaning that the final
'value of mcol is correct.
'* NOTE: If there is no metals concentration data, then a metal is assigned to be of
'* "0" % in the "PercentileA" and "PercentileS"  worksheet tables.  The "matrix" worksheet table,
outputs '* a "0" % value to be a "nodata" contamination threat.

'FOR THE A SOIL HORIZON
         If Worksheets("A_Soils").Cells(i, j) <= Worksheets("PercentileA").Cells(7 - k, j - 4)
Then 'mcol is used to reference the correct column in "Matrix". Again, the percentile classes
'are encountered in reverse order, in order to agree with the "PercentileA" worksheet 'mrow is
always 4 as there is only 1 row in the matrix
            mcol = 8 - k
            mrow = 4
         End If
       Next k
'Output A soil metal concentrations threat, from correct column of the matrix
         Worksheets("Step4_OutputA").Cells(i, j - 2) = Worksheets("Matrix").Cells(mrow, mcol)


'REPEAT PROCESS FOR THE S SOIL HORIZON
      For k = 1 To 5
         If Worksheets("S_Soils").Cells(i, j) <= Worksheets("PercentileS").Cells(7 - k, j - 4) Then
            mcol = 8 - k
            mrow = 4
```

```
            End If
        Next k
'Output S soil metal concentrations threat, from correct column of the matrix
        Worksheets("Step4_OutputS").Cells(i, j - 2) = Worksheets("Matrix").Cells(mrow, mcol)

End If

End Sub
Sub OverallRisk(i, j)
'****************************************************************************
'This subroutine compares the output for the A and S soil horizons and the highest threat
'category is output to worksheet "Step4_OverallOutput".
'****************************************************************************

        If Worksheets("Step4_OutputA").Cells(i, j) = "L" Or Worksheets("Step4_OutputS").Cells(i,
j) = "L" Then
            Worksheets("Step4_OverallOutput").Cells(i, j) = "L"
        End If

        If Worksheets("Step4_OutputA").Cells(i, j) = "M" Or
Worksheets("Step4_OutputS").Cells(i, j) = "M" Then
            Worksheets("Step4_OverallOutput").Cells(i, j) = "M"
        End If

        If Worksheets("Step4_OutputA").Cells(i, j) = "H" Or
Worksheets("Step4_OutputS").Cells(i, j) = "H" Then
            Worksheets("Step4_OverallOutput").Cells(i, j) = "H"
        End If


'The value for the "A" horizon is used where both values are equal
        If Worksheets("Step4_OutputA").Cells(i, j) = Worksheets("Step4_OutputS").Cells(i, j)
Then
            Worksheets("Step4_OverallOutput").Cells(i, j) = Worksheets("Step4_OutputA").Cells(i,
j)
        End If

'* NOTE: If the values for either the A or S soil horizon is an error message,
'* denoting missing data, then the model will output the error warning, and not
'* the threat, calculated from just one soil horizon.

        If Worksheets("Step4_OutputA").Cells(i, j) = "nodata" Or
Worksheets("Step4_OutputS").Cells(i, j) = "nodata" Then
            Worksheets("Step4_OverallOutput").Cells(i, j) = "nodata"
        End If

        If Worksheets("Step4_OutputA").Cells(i, j) = "na" Or
Worksheets("Step4_OutputS").Cells(i, j) = "na" Then
            Worksheets("Step4_OverallOutput").Cells(i, j) = "na"
        End If


End Sub
```

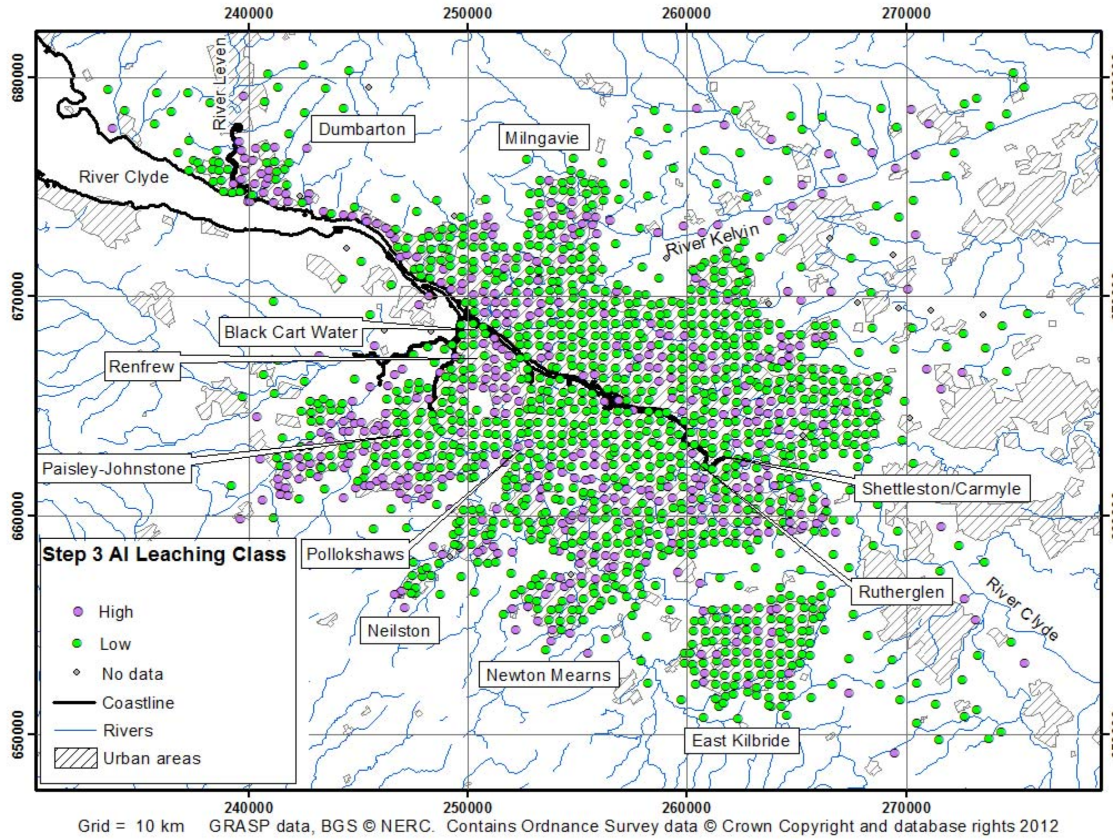
```
Sub CombinedClass(i, j)
'***************************************************************************
'This subroutine combines the final soil concentration class (for both topsoil and subsoil)
'with the leaching potential threat calculated from Step 3, according to the matrix shown in
'Table 8 of the GRASP methodology.
'The final prioritisation class is output to worksheet "Step4_CombinedPriorityClass".
'***************************************************************************

    If Worksheets("Step3_Rank").Cells(i, j) = "L" Or
Worksheets("Step4_OverallOutput").Cells(i, j) = "L" Then
        Worksheets("Step4_CombinedPriorityClass").Cells(i, j) = "L"
    End If

    If Worksheets("Step3_Rank").Cells(i, j) = "M" Or
Worksheets("Step4_OverallOutput").Cells(i, j) = "M" Then
        Worksheets("Step4_CombinedPriorityClass").Cells(i, j) = "M"
    End If

    If Worksheets("Step3_Rank").Cells(i, j) = "H" Or
Worksheets("Step4_OverallOutput").Cells(i, j) = "H" Then
        Worksheets("Step4_CombinedPriorityClass").Cells(i, j) = "H"
    End If

    If Worksheets("Step3_Rank").Cells(i, j) = "H" And
Worksheets("Step4_OverallOutput").Cells(i, j) = "H" Then
        Worksheets("Step4_CombinedPriorityClass").Cells(i, j) = "VH"
    End If

'* NOTE: If the values for either the A or S soil horizon is an error message,
'* denoting missing data, then the model will output the error warning, and not
'* the threat, calculated from just one soil horizon.

    If Worksheets("Step3_Rank").Cells(i, j) = "nodata" Or
Worksheets("Step4_OverallOutput").Cells(i, j) = "nodata" Then
        Worksheets("Step4_CombinedPriorityClass").Cells(i, j) = "nodata"
    End If

    If Worksheets("Step3_Rank").Cells(i, j) = "na" Or
Worksheets("Step4_OverallOutput").Cells(i, j) = "na" Then
        Worksheets("Step4_CombinedPriorityClass").Cells(i, j) = "na"
    End If
End Sub
```

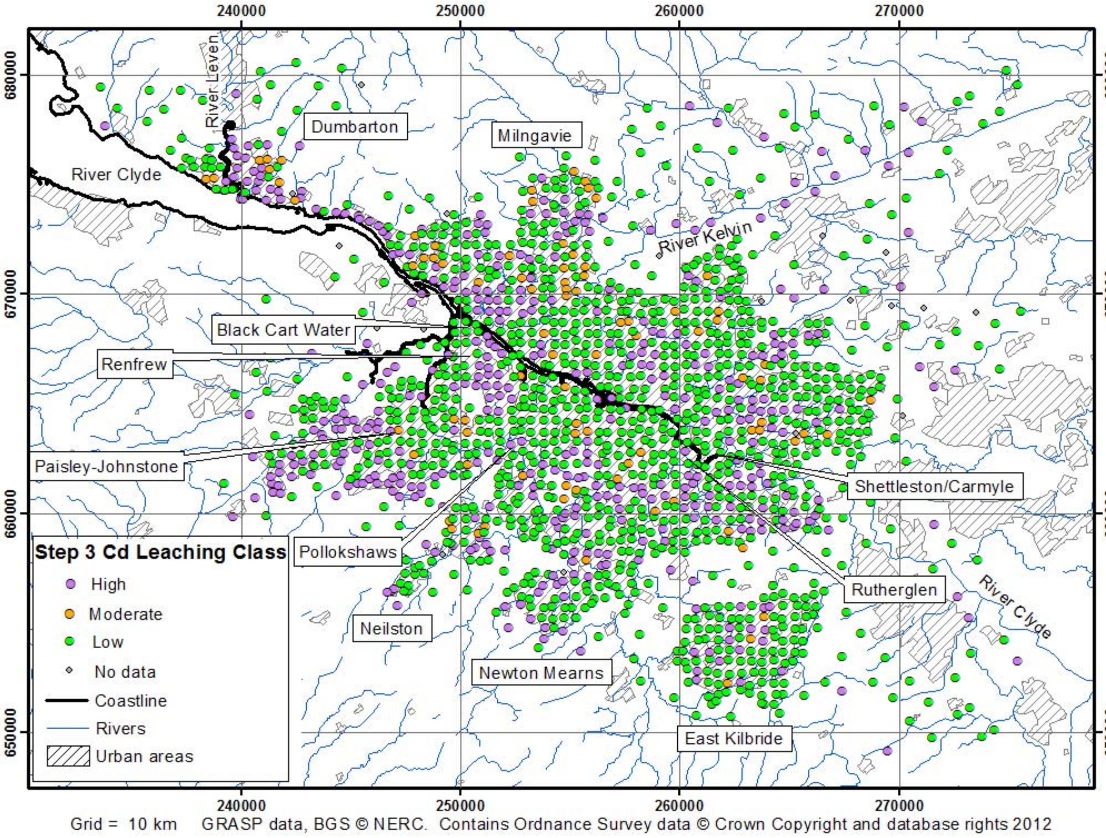
Appendix 2 GRASP Leaching Potential Maps from Step 3

The latest version of the GRASP GIS is held in the following BGS corporate data folder:
W:\Teams\RSS\Clyde_Basin\Data\Hydrogeology\Data\GRASP\GIS_development\refinements Grasp_redo3.mxd.

The latest outputs from the GIS are held in the following folder:
W:\Teams\RSS\Clyde_Basin\Data\Hydrogeology\Data\GRASP\GIS_development\refinements\newoutputs\Aug2013

The following ten maps show the output from Step 3 of GRASP, namely leaching potential rankings for the ten metals Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn




Step 3 Cd Leaching Class
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Dumbarton
Milngavie
River Clyde
River Leven
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
Neilston
Newton Mearns
East Kilbride
240000
250000
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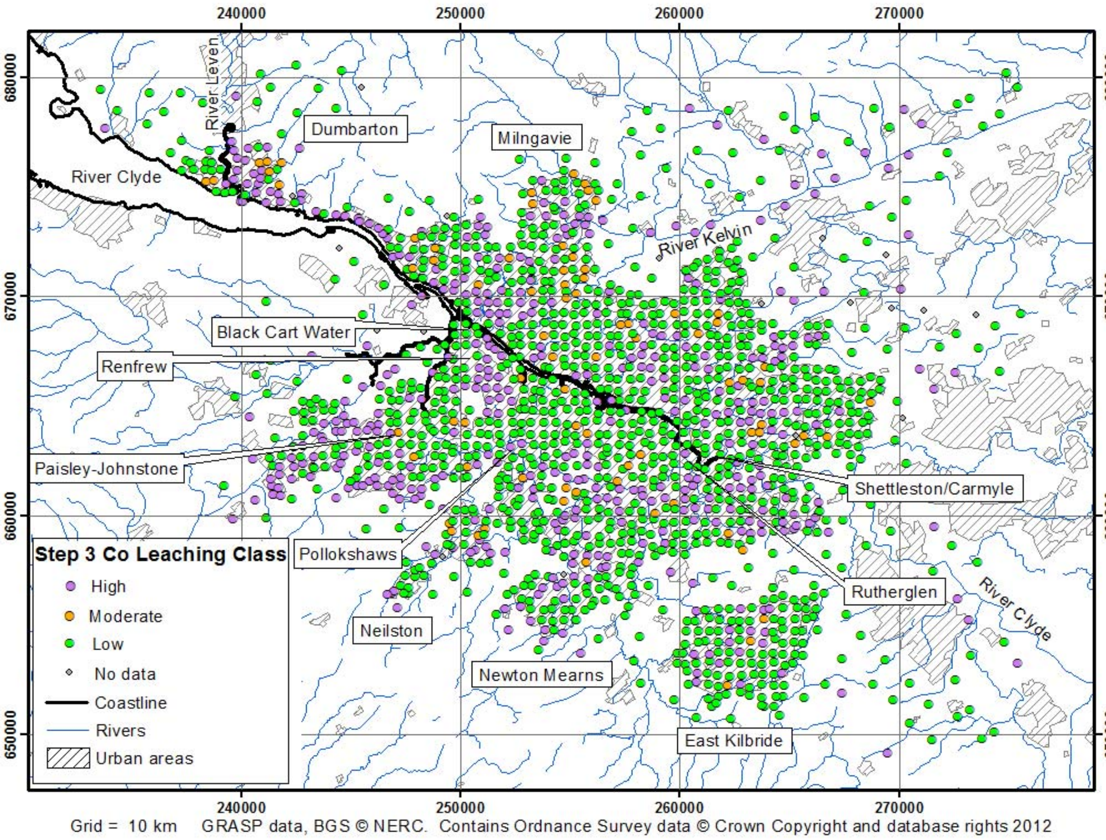
680000
670000
660000
650000
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012


Step 3 Co Leaching Class
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Dumbarton
Milngavie
River Clyde
River Leven
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
Neilston
Newton Mearns
East Kilbride
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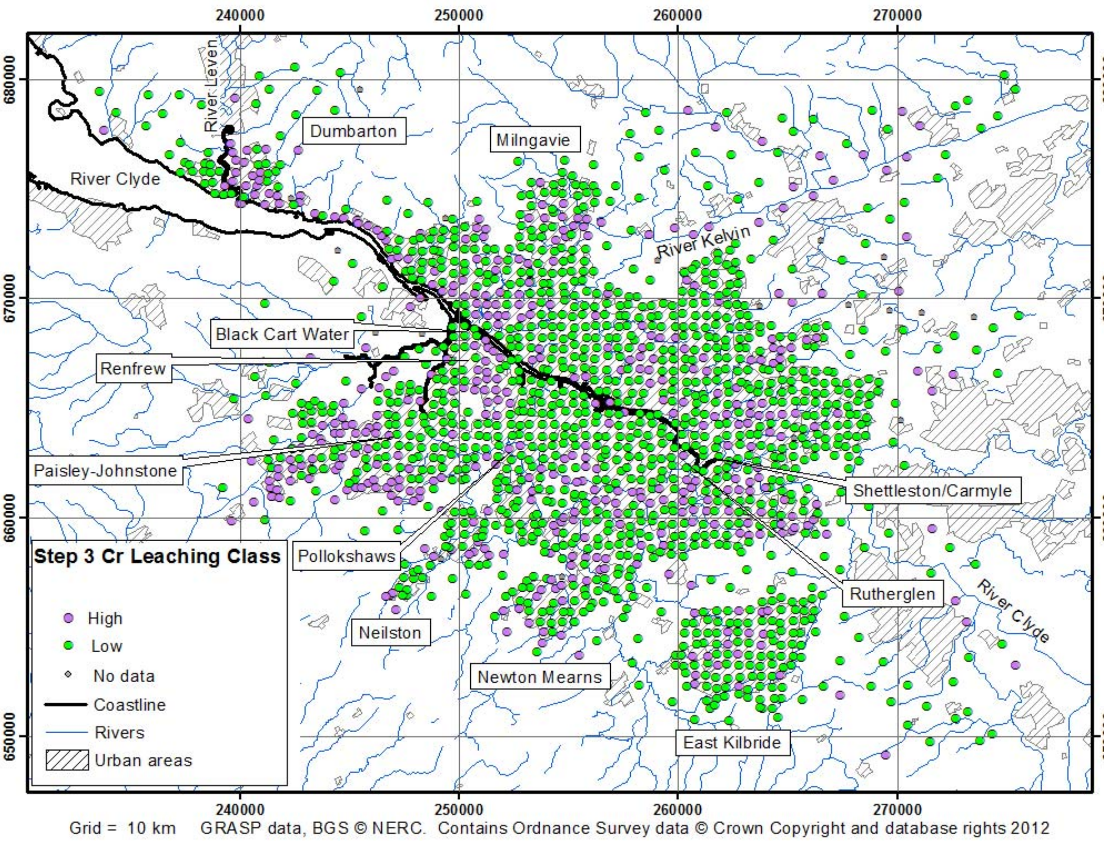
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



240000
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680000
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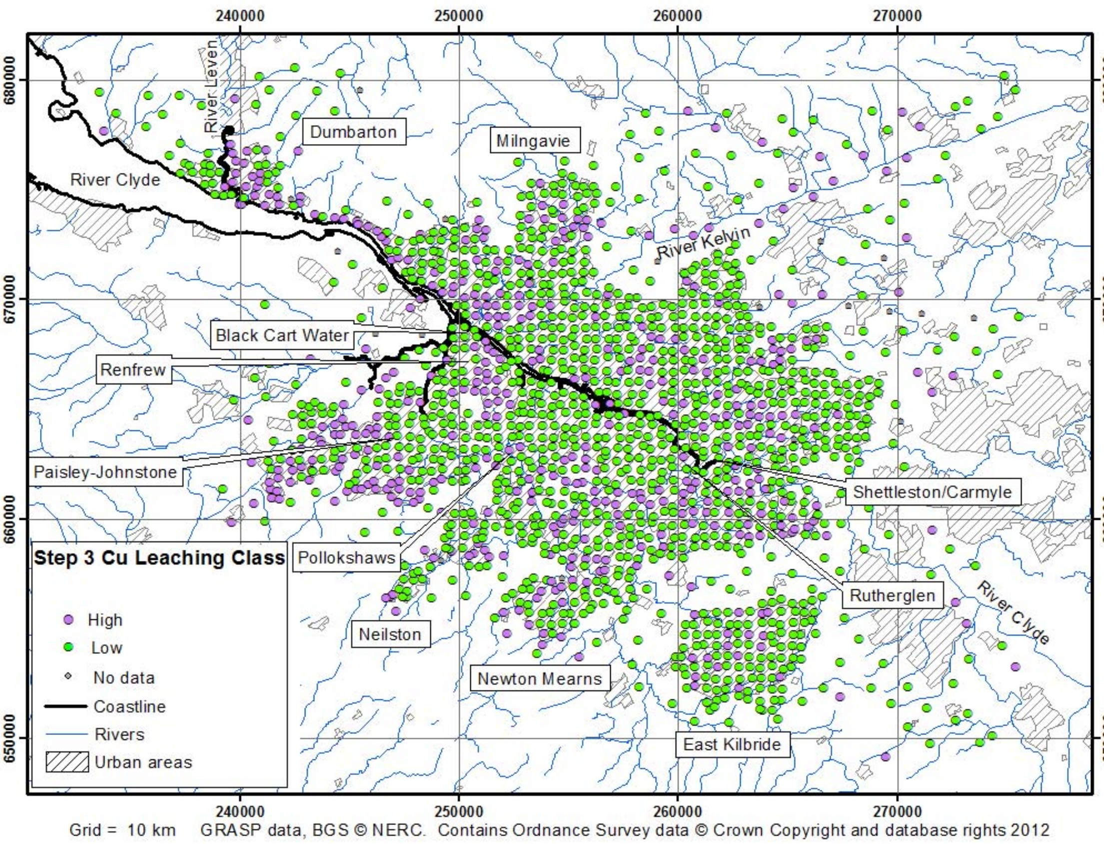
660000
650000
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
Neilston
Newton Mearns
East Kilbride
Step 3 Cr Leaching Class
High
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



240000
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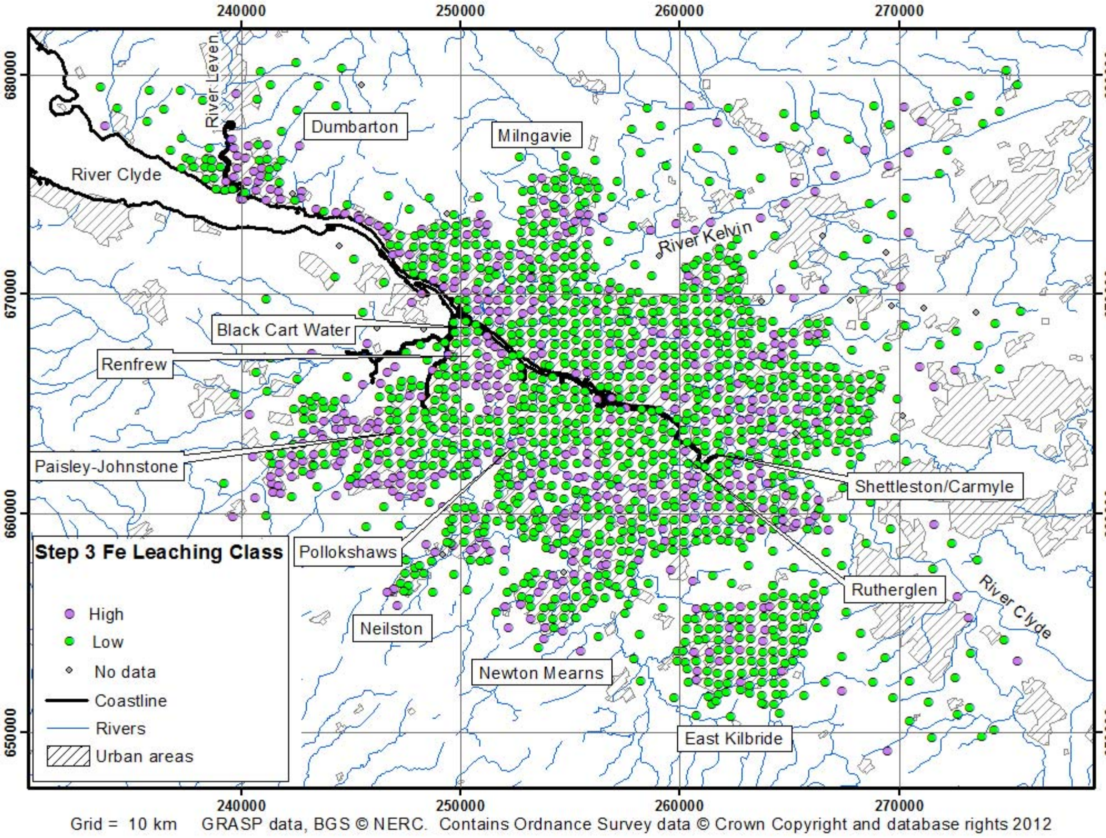
650000
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
Neilston
Newton Mearns
East Kilbride
Step 3 Cu Leaching Class
High
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012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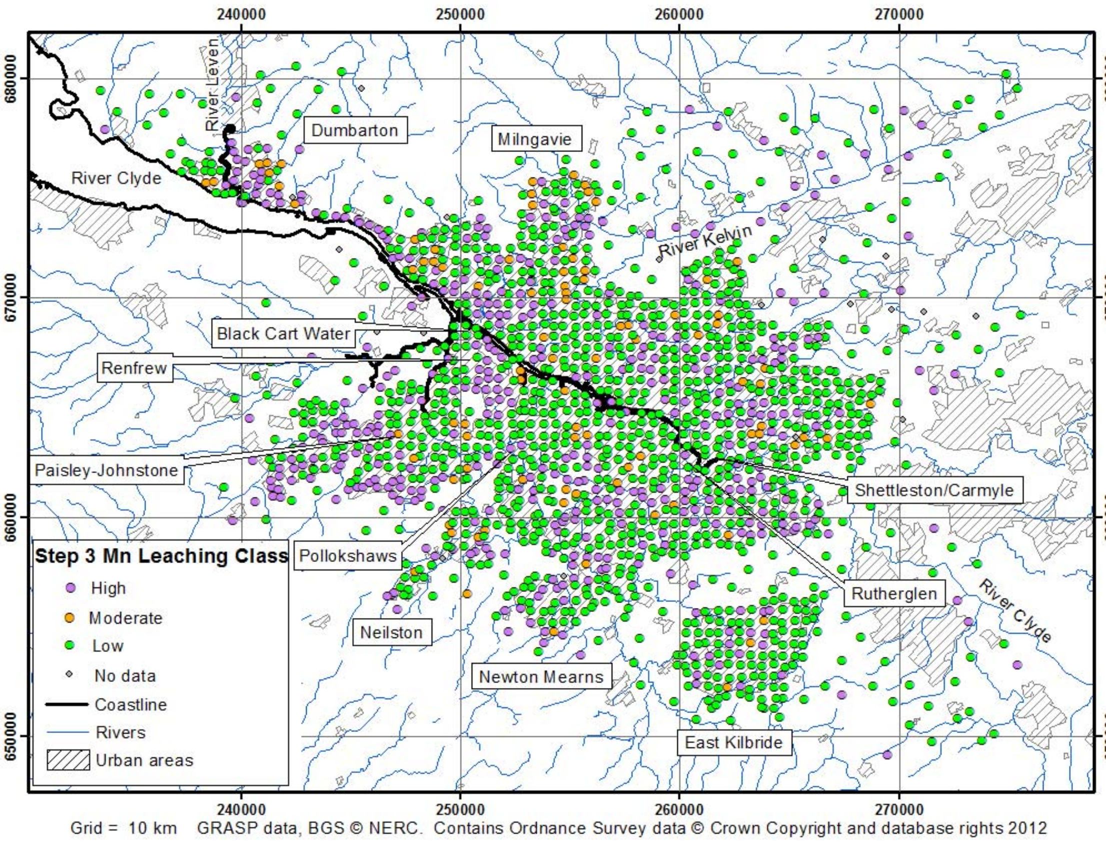
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
River Clyde
Neilston
Newton Mearns
East Kilbride
Step 3 Fe Leaching Class
High
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012


240000
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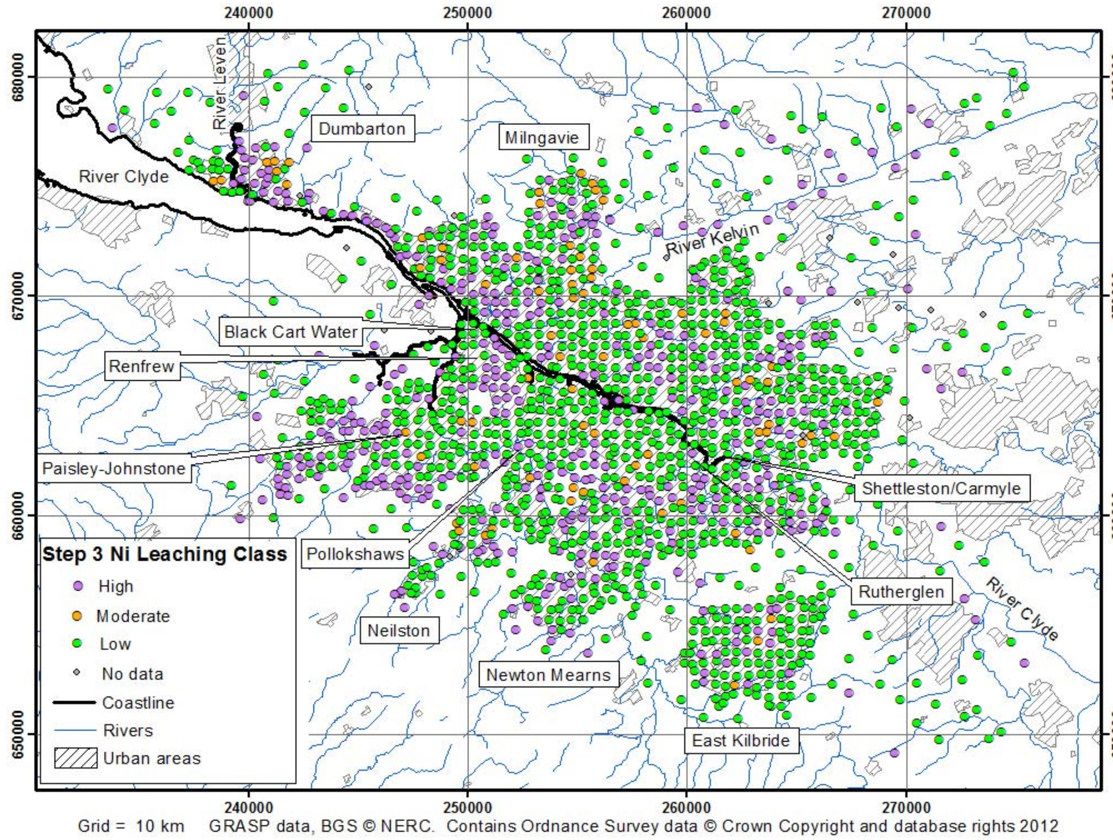
660000
650000
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
River Clyde
Neilston
Newton Mearns
East Kilbride
Step 3 Mn Leaching Class
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012


240000
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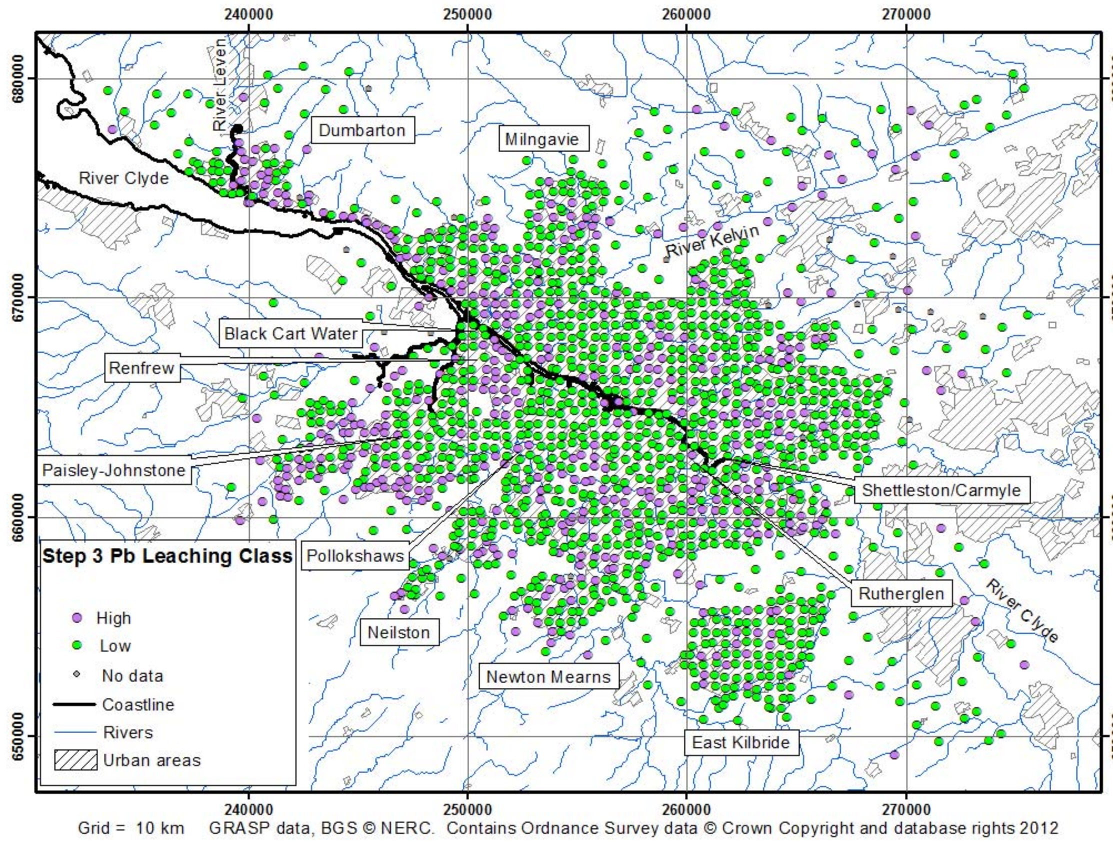
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
River Clyde
Neilston
Newton Mearns
East Kilbride
Step 3 Ni Leaching Class
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012


240000
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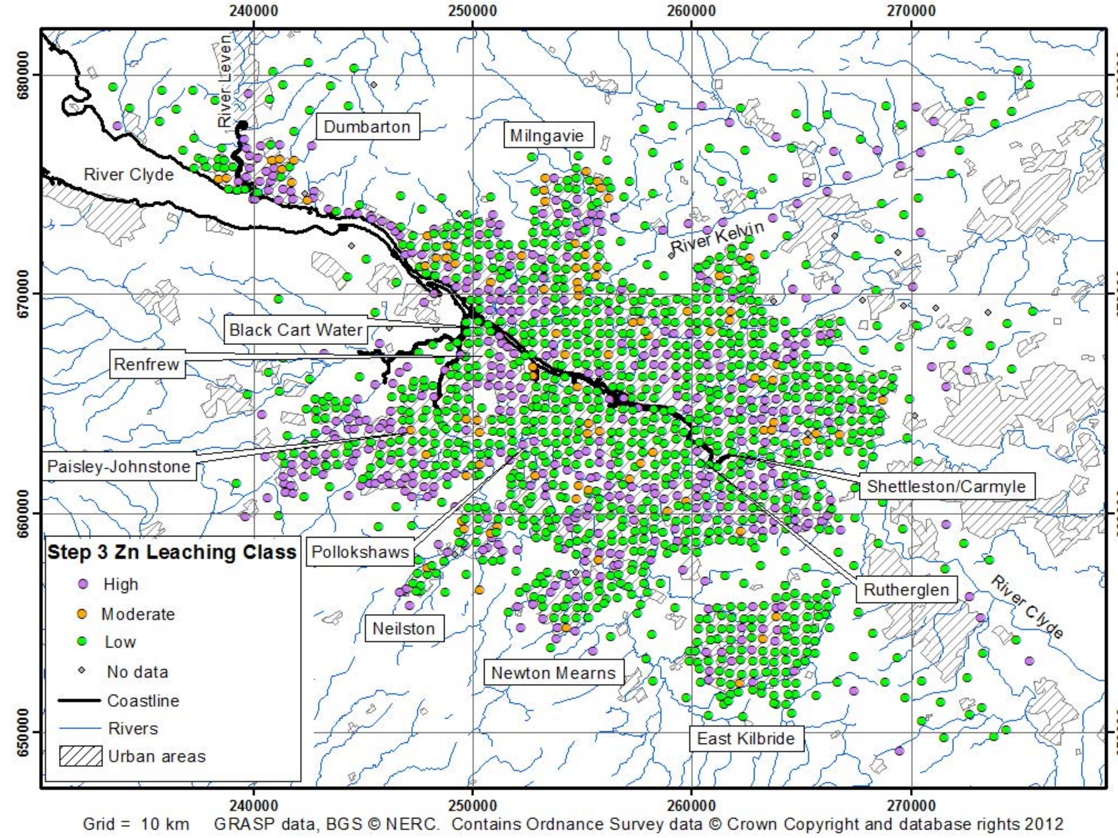
650000
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
River Clyde
Neilston
Newton Mearns
East Kilbride
Step 3 Pb Leaching Class
High
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012


Step 3 Zn Leaching Class
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Dumbarton
Milngavie
River Leven
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
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Rutherglen
Neilston
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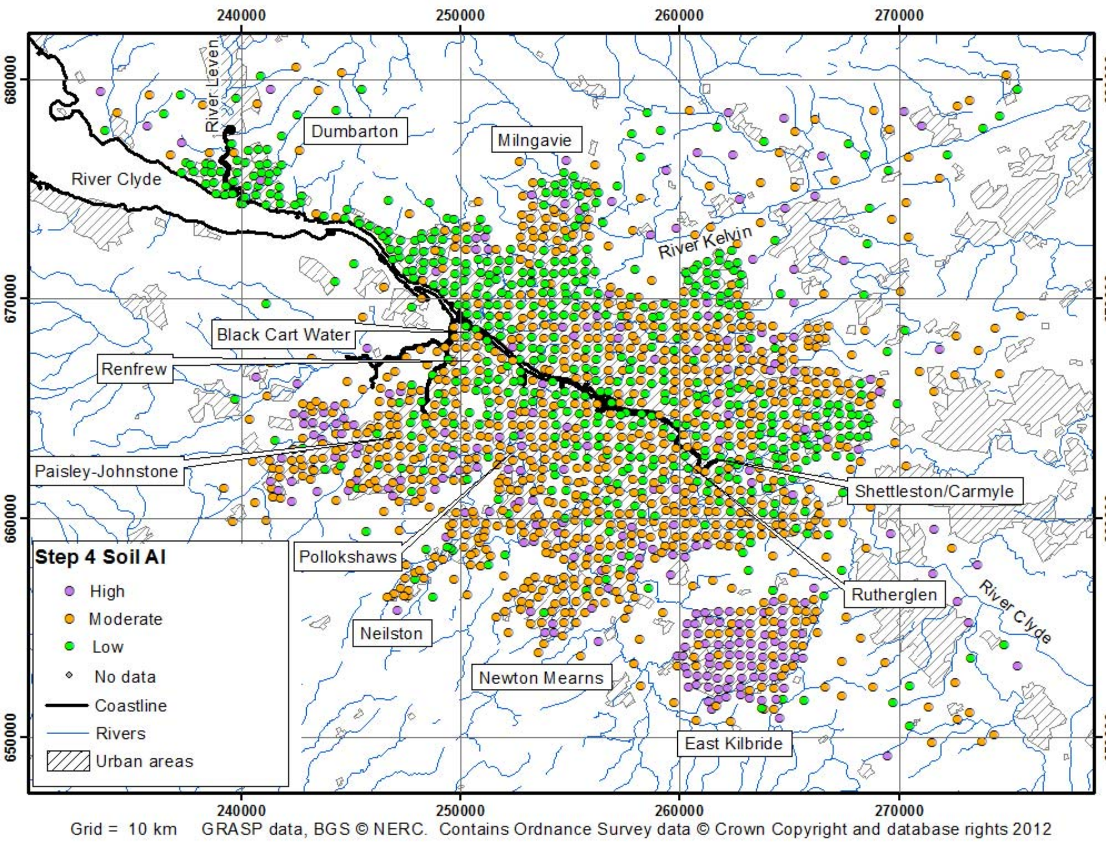
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012

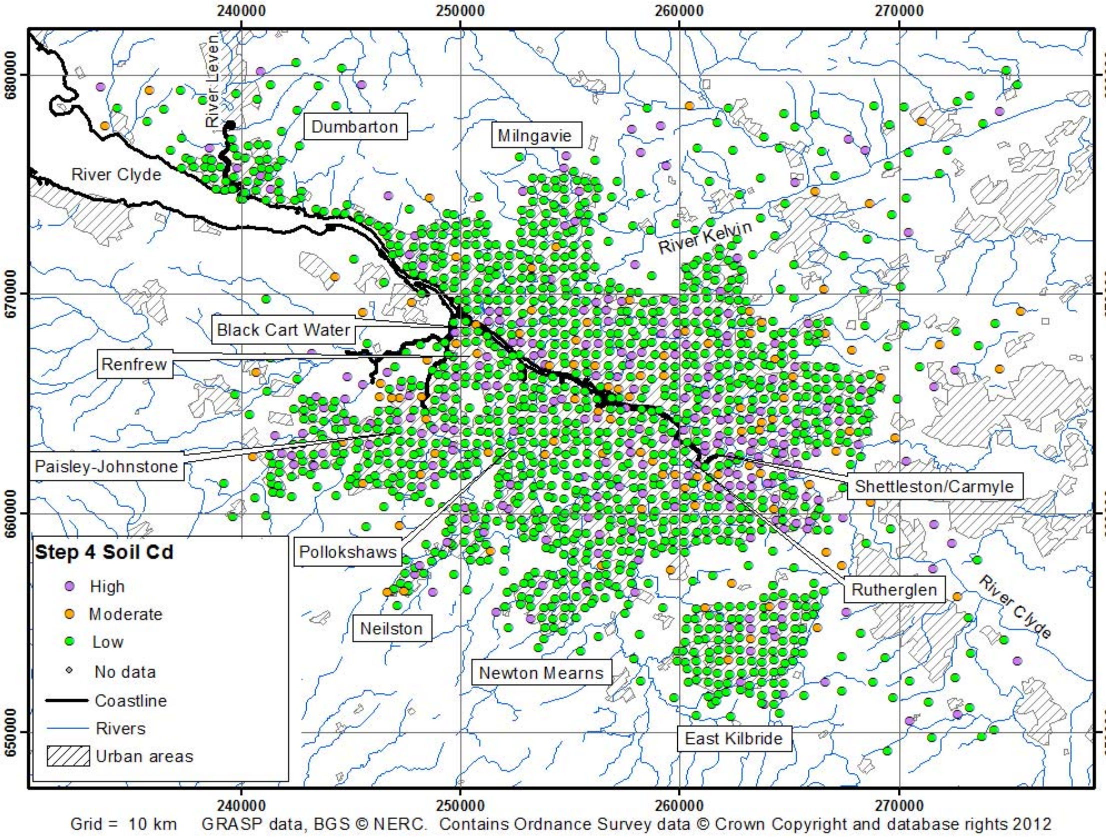
Appendix 3 GRASP Metal Concentration Classification Maps from Step 4

The latest version of the GRASP GIS is held in the following BGS corporate data folder: W:\Teams\RSS\Clyde_Basin\Data\Hydrogeology\Data\GRASP\GIS_development\refinements Grasp_redo3.mxd.

The latest outputs from the GIS are held in the following folder: W:\Teams\RSS\Clyde_Basin\Data\Hydrogeology\Data\GRASP\GIS_development\refinements\newoutputs\Aug2013

The following ten maps show the output from the soil metal concentration classification in Step 4 of the revised version of GRASP, namely threat rankings for the ten metals Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn.





240000
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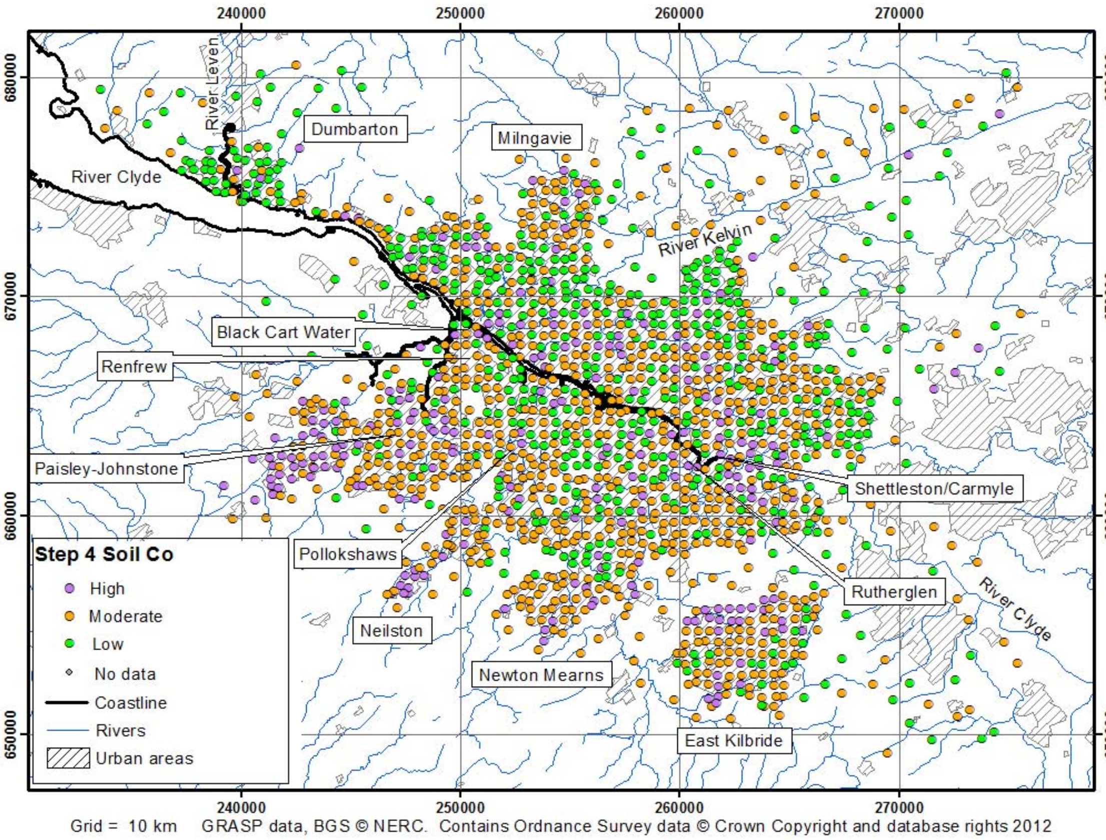
650000
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
Neilston
Newton Mearns
East Kilbride
Step 4 Soil Cd
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



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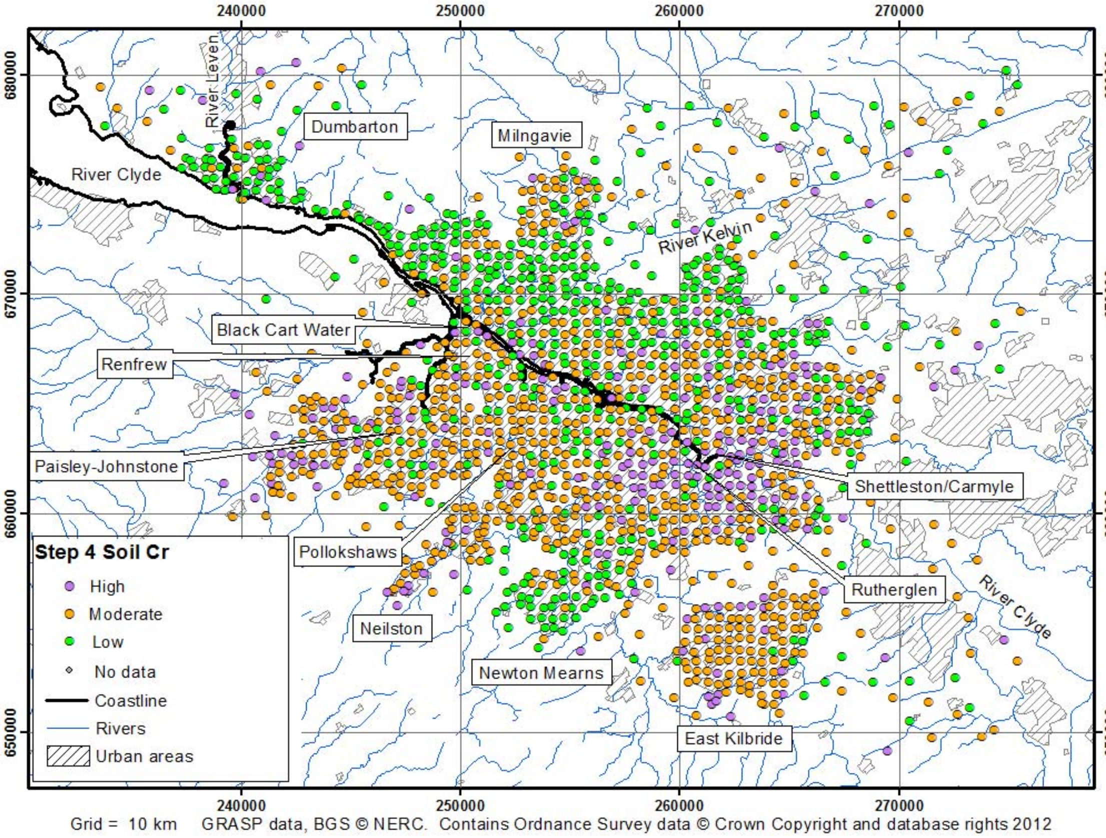
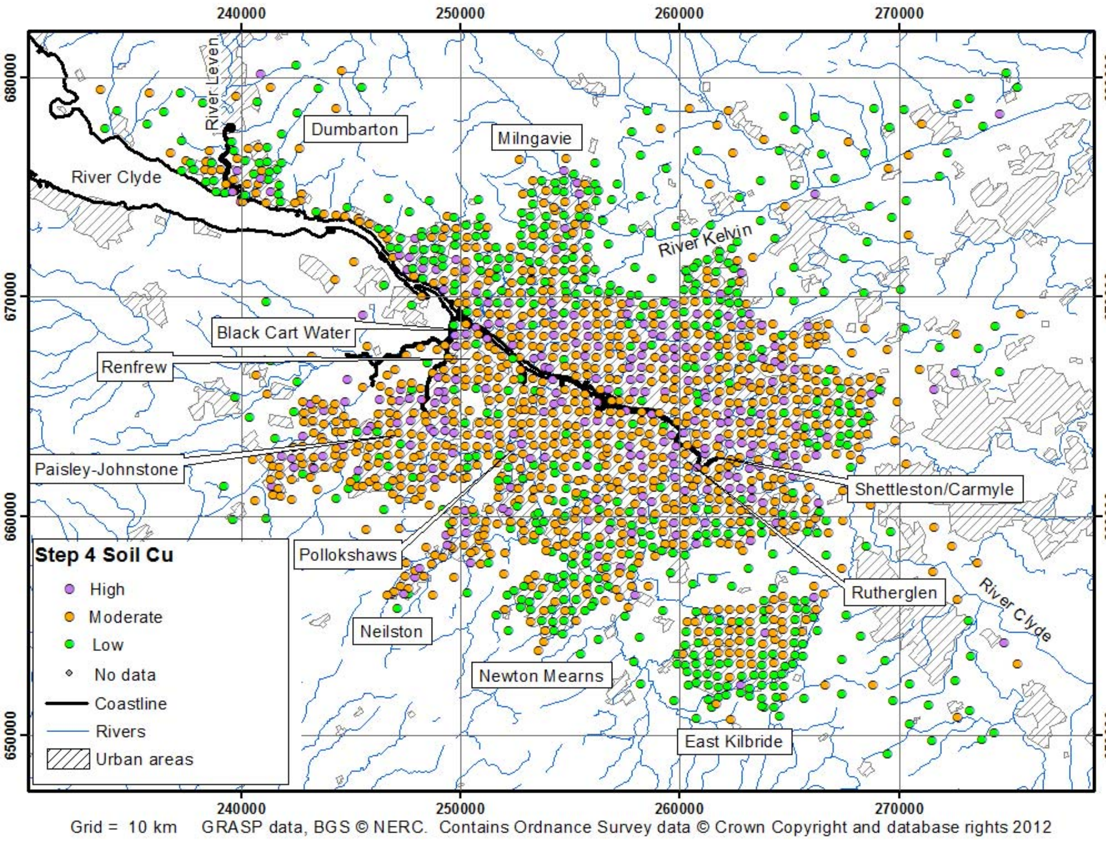
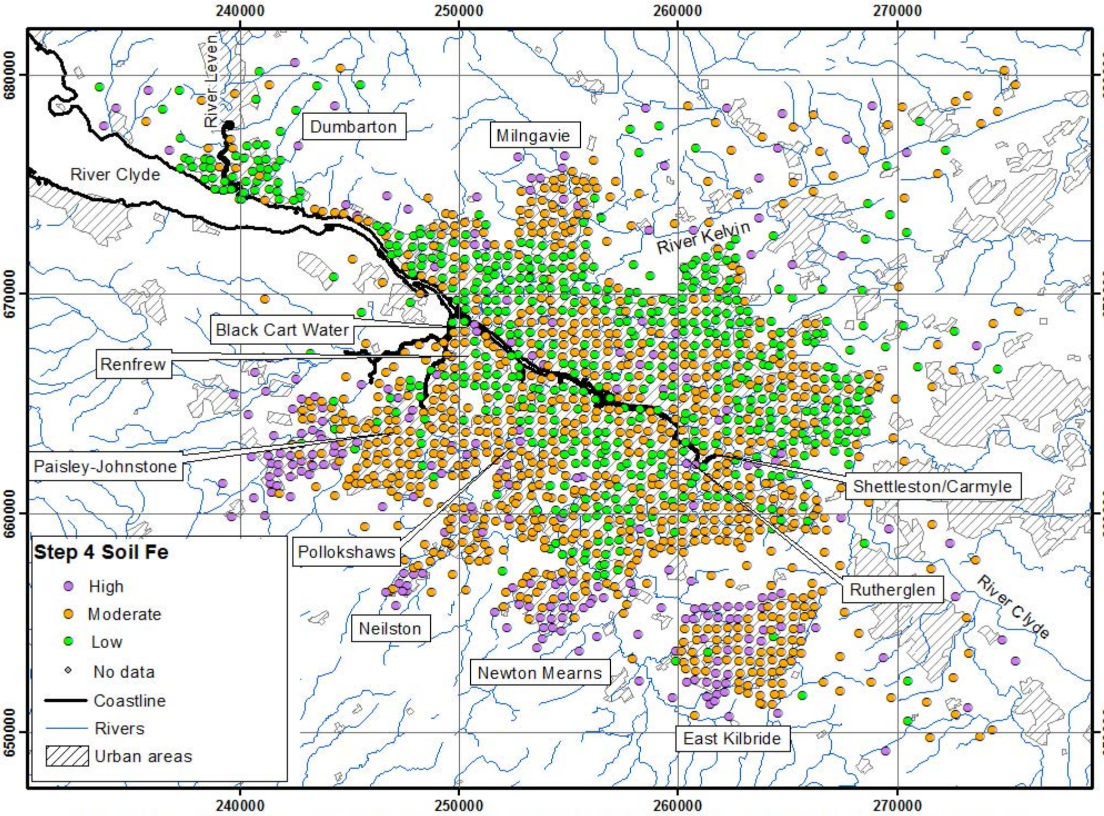
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
Neilston
Newton Mearns
East Kilbride
Step 4 Soil Co
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



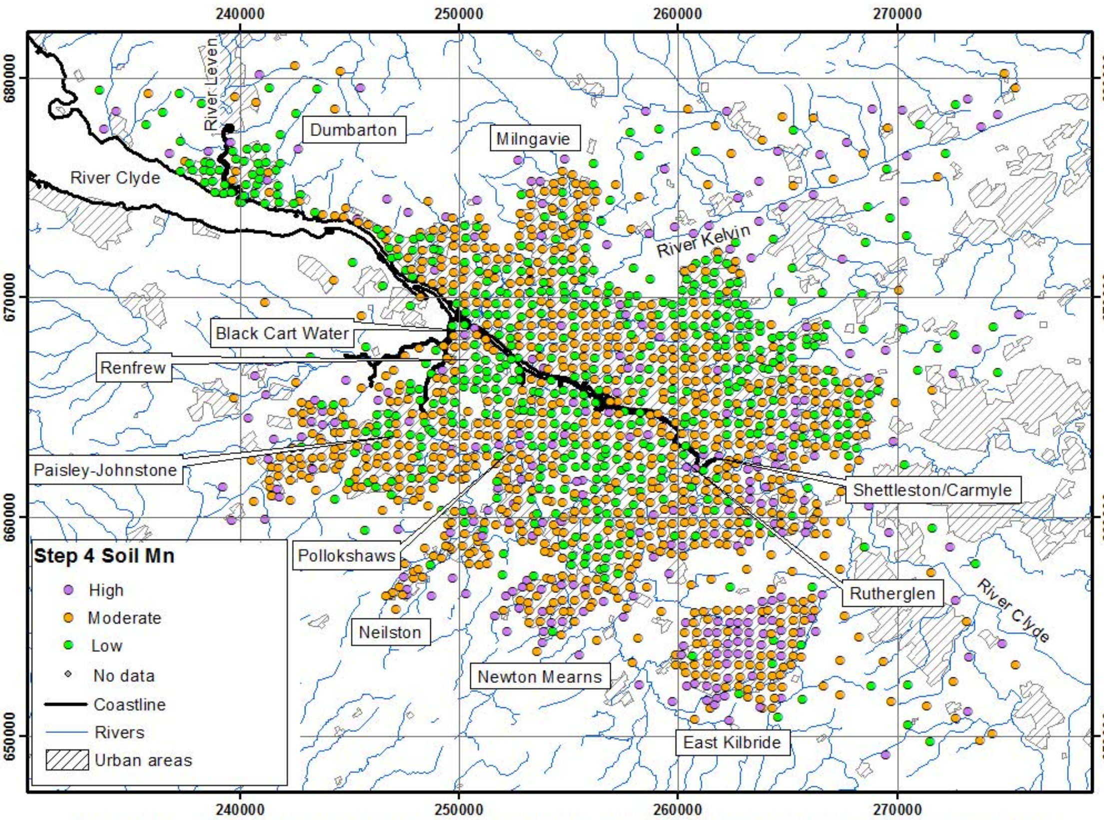
Step 4 Soil Cr
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
Neilston
Newton Mearns
East Kilbride
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



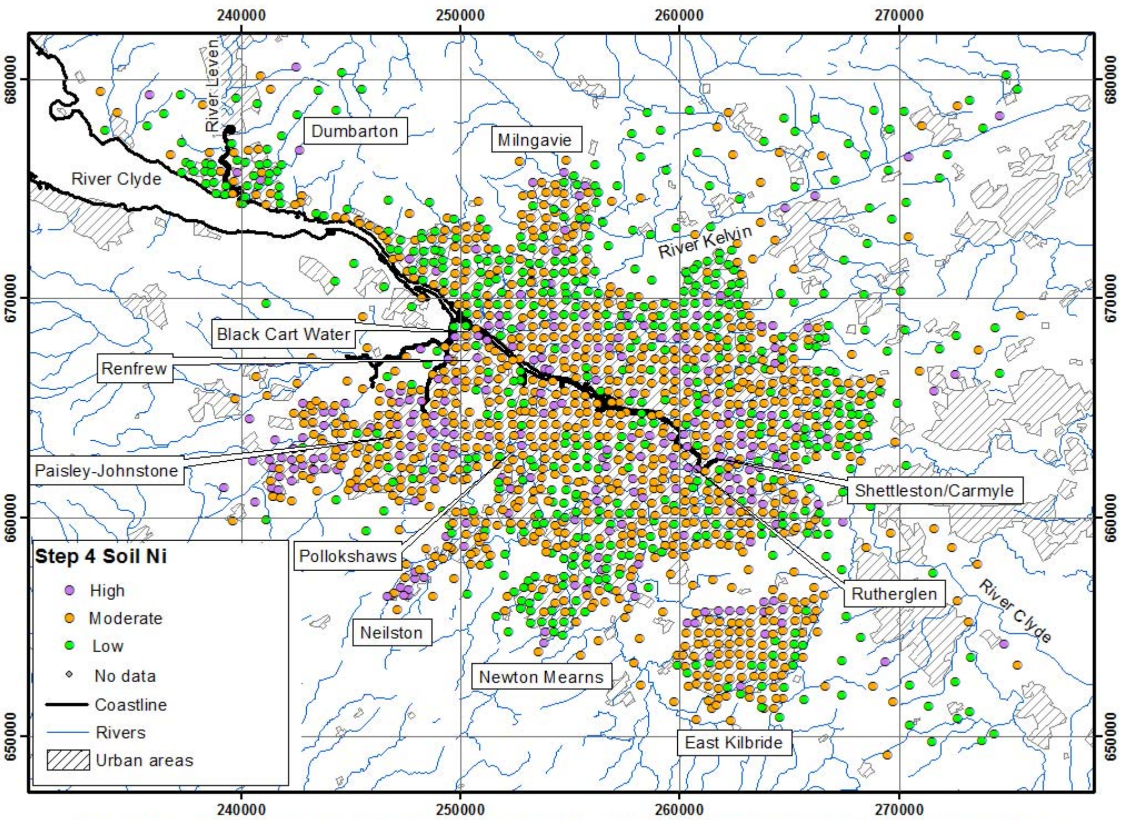
Step 4 Soil Cu
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
Neilston
Newton Mearns
East Kilbride
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



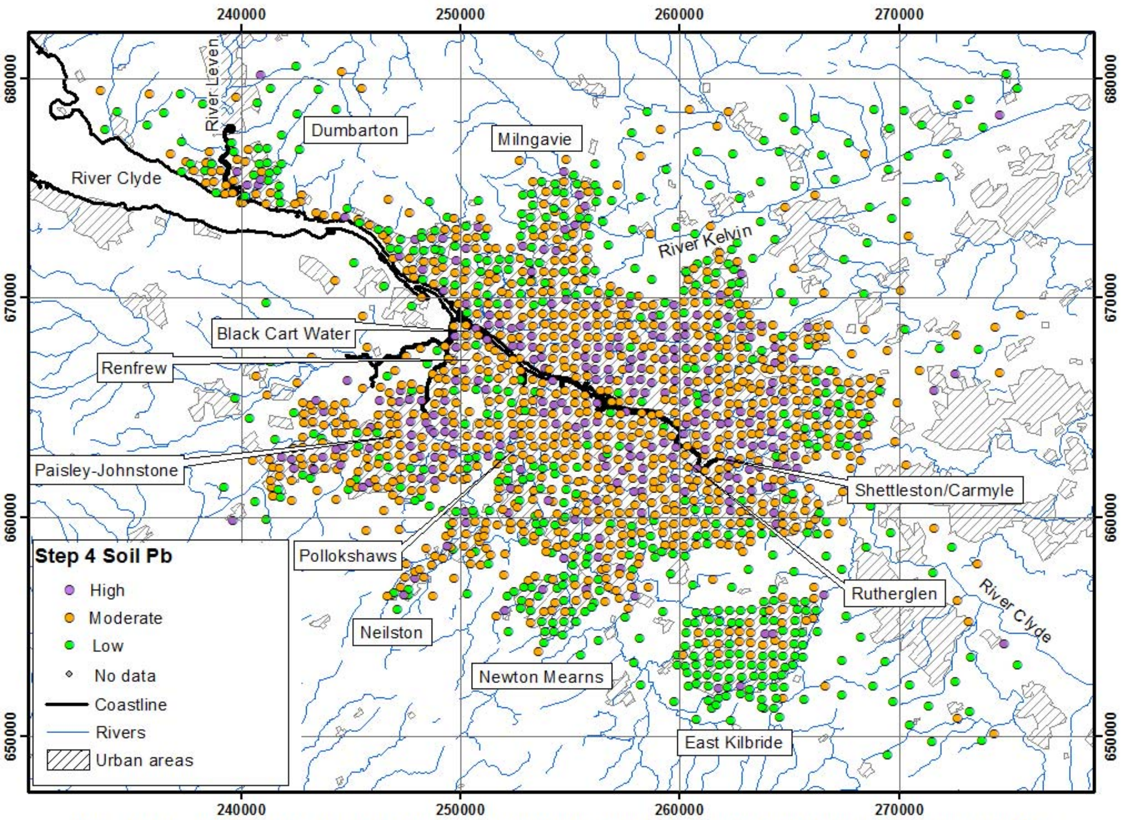
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



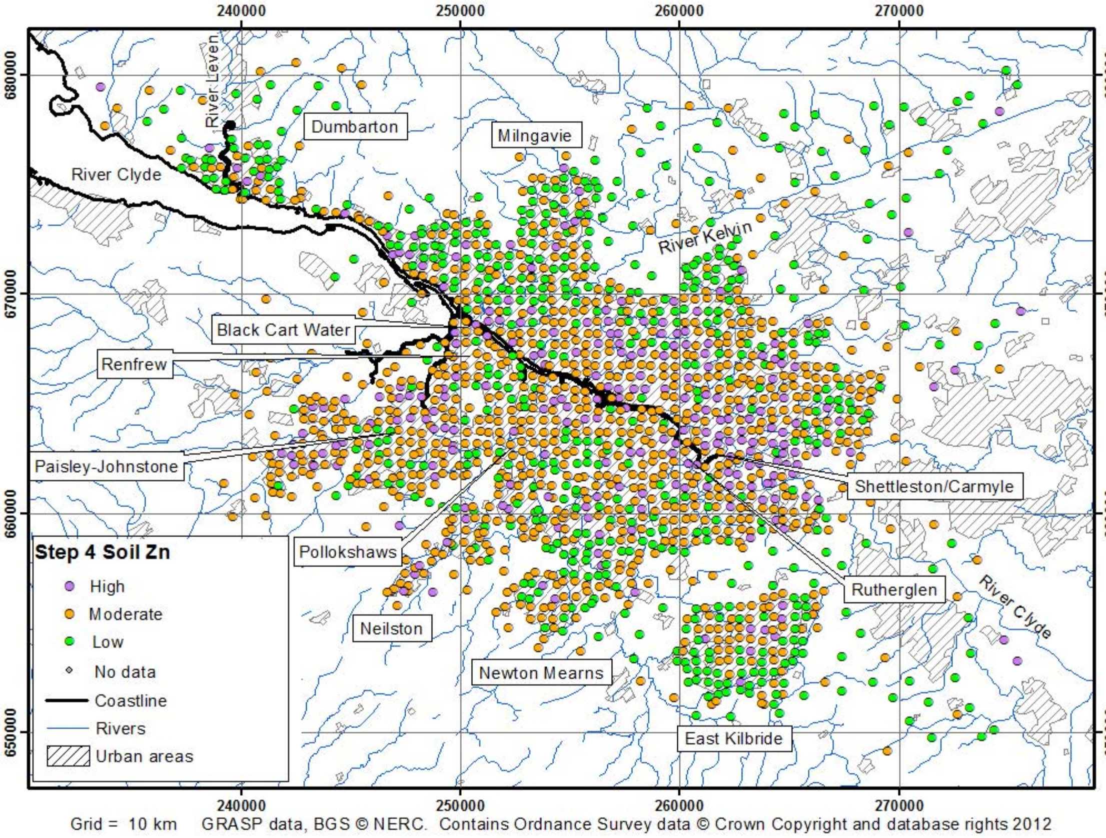
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



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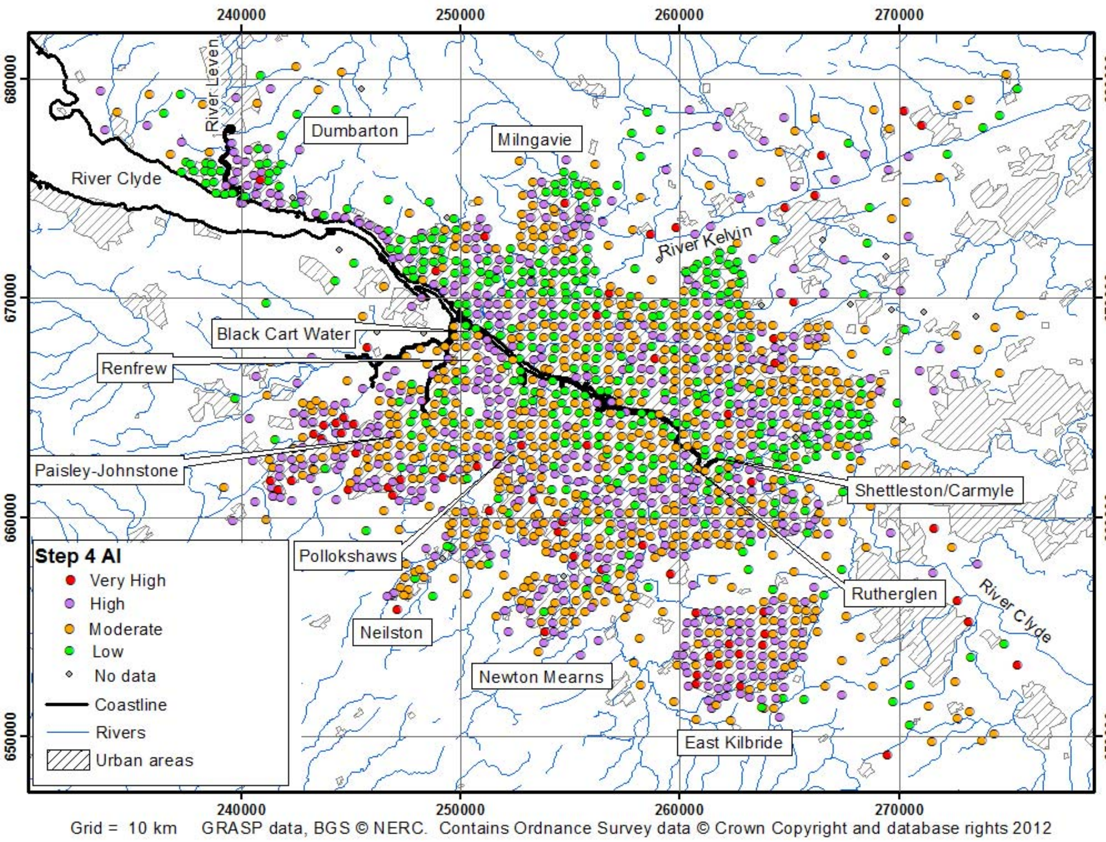
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
River Clyde
Neilston
Newton Mearns
East Kilbride
Step 4 Soil Zn
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012

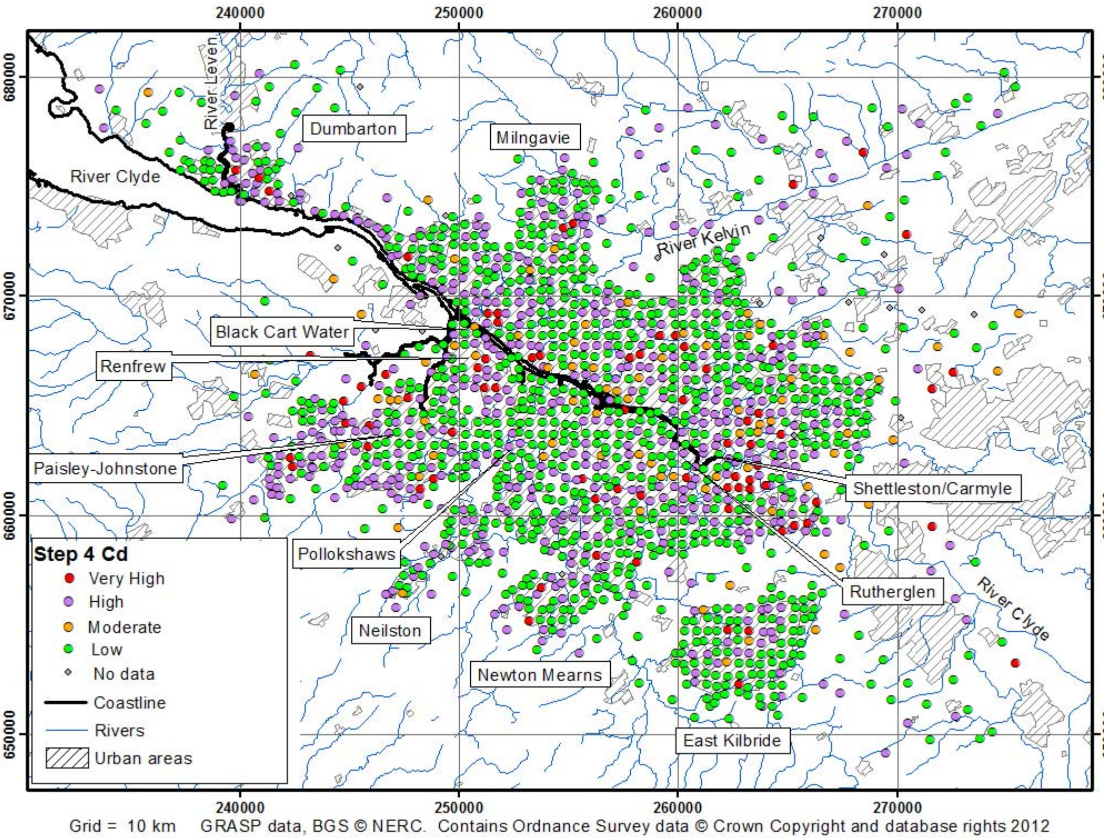
Appendix 4 GRASP Prioritisation Ranking Maps from Step 4

The latest version of the GRASP GIS is held in the following BGS corporate data folder:
W:\Teams\RSS\Clyde_Basin\Data\Hydrogeology\Data\GRASP\GIS_development\refinements
Grasp_redo3.mxd.

The latest outputs from the GIS are held in the following folder:
W:\Teams\RSS\Clyde_Basin\Data\Hydrogeology\Data\GRASP\GIS_development\refinements\newoutputs\Aug2013

The following ten maps show the output from the combined soil metal concentration and leaching potential classification in Step 4 of the revised version of GRASP, namely prioritisation rankings for the ten metals Al, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn.





240000
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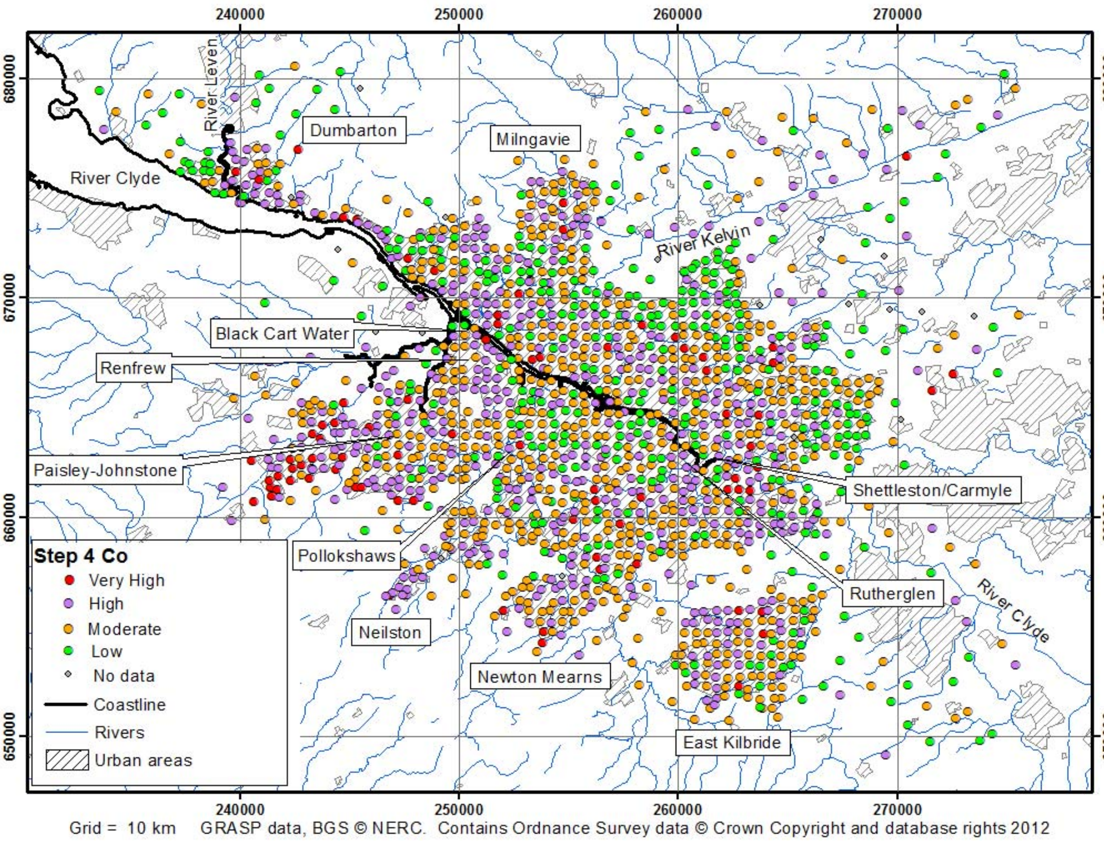
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
River Clyde
Neilston
Newton Mearns
East Kilbride
Step 4 Cd
Very High
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



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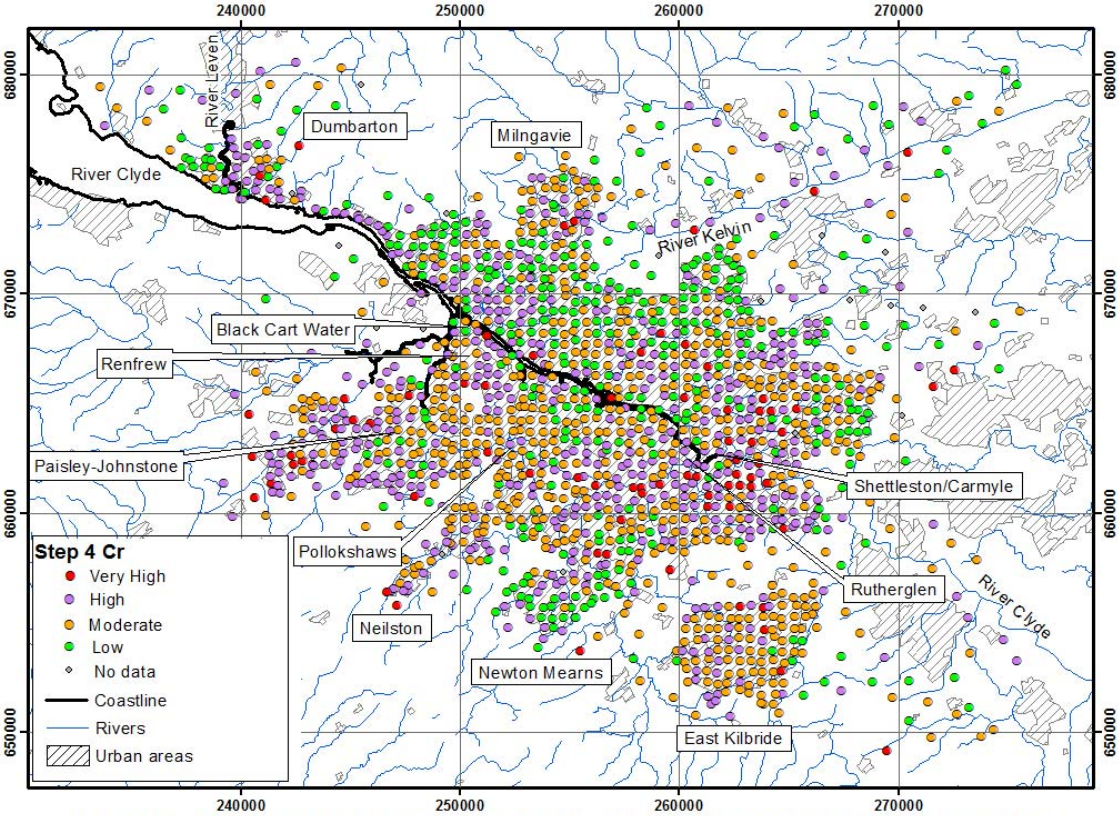
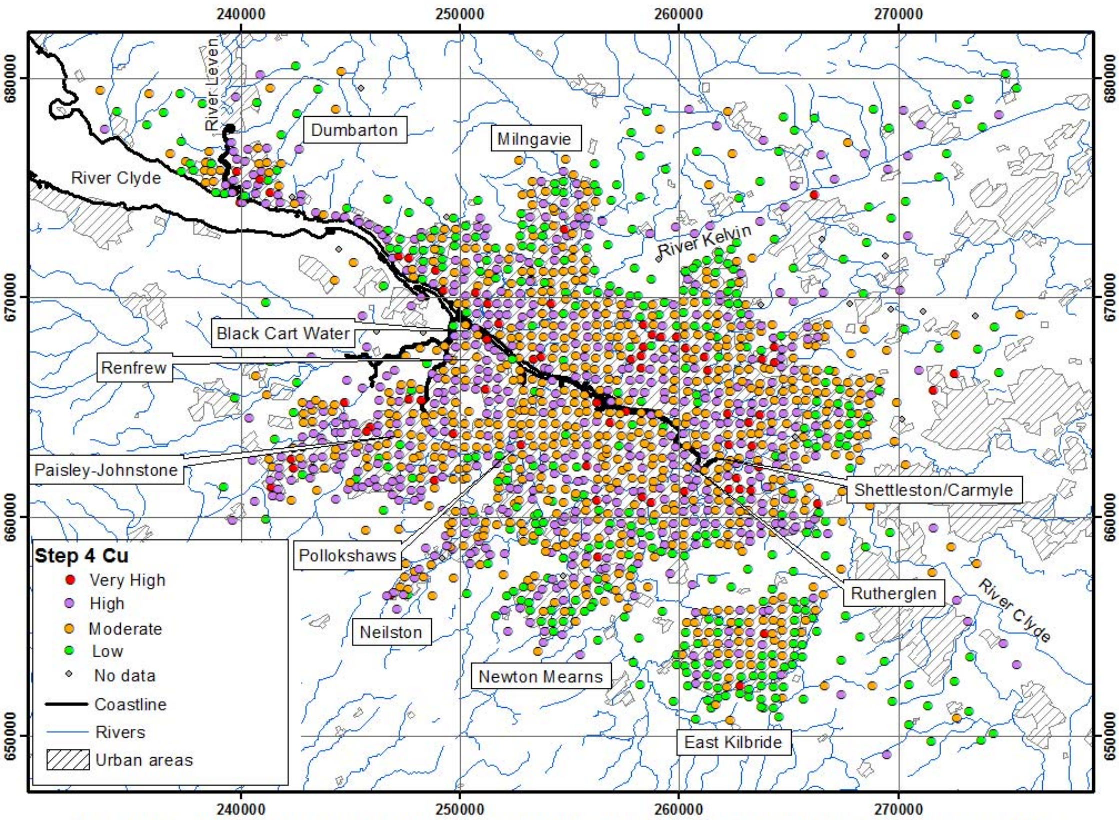
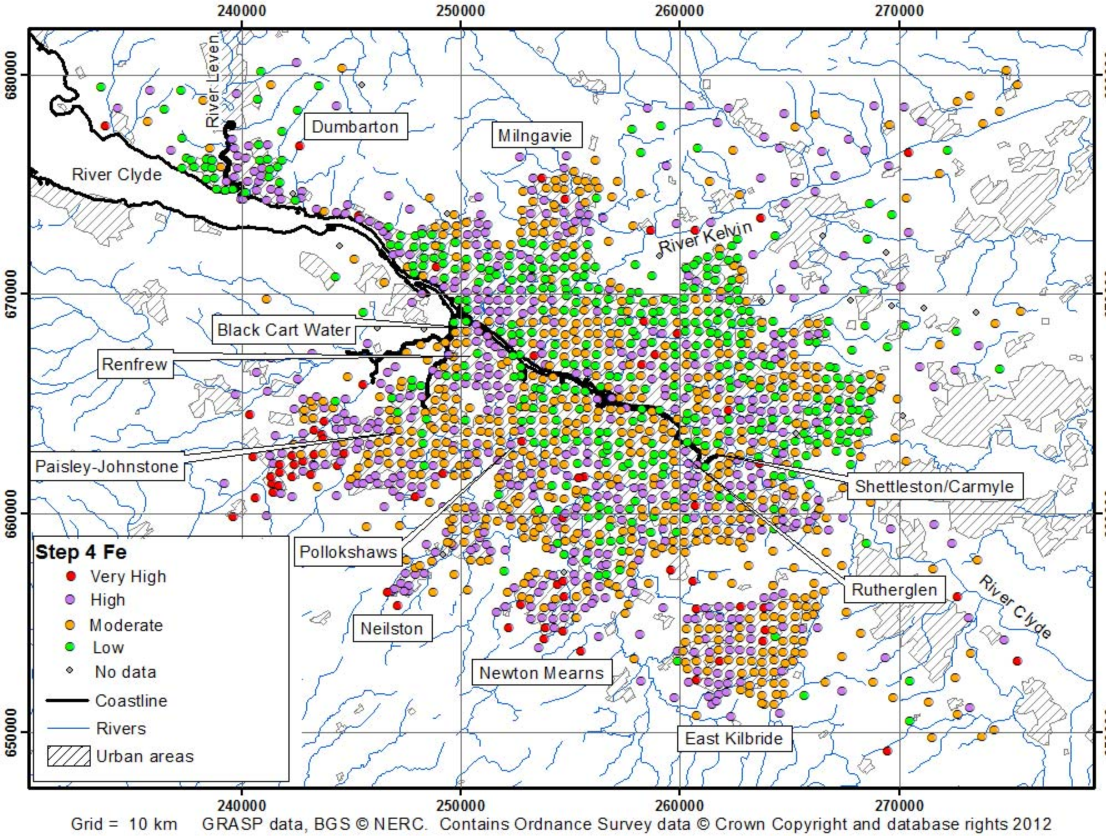
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
River Clyde
Neilston
Newton Mearns
East Kilbride
Step 4 Co
Very High
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012

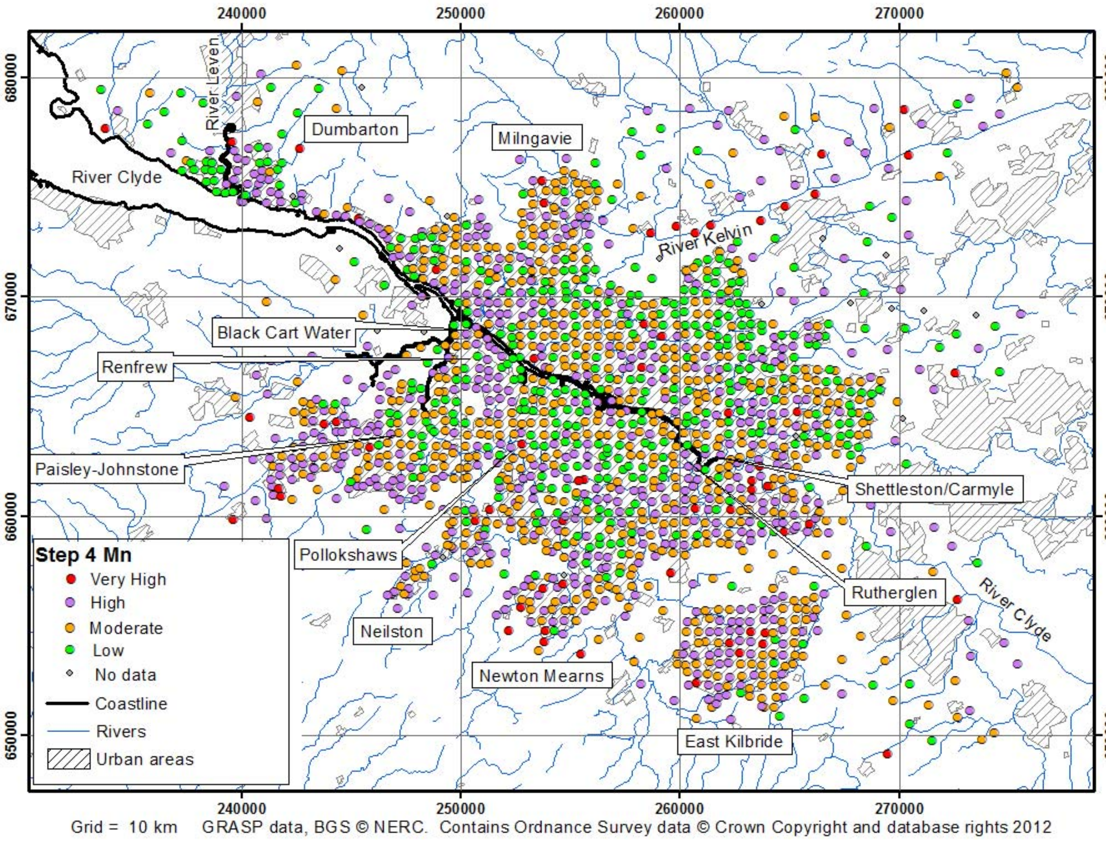


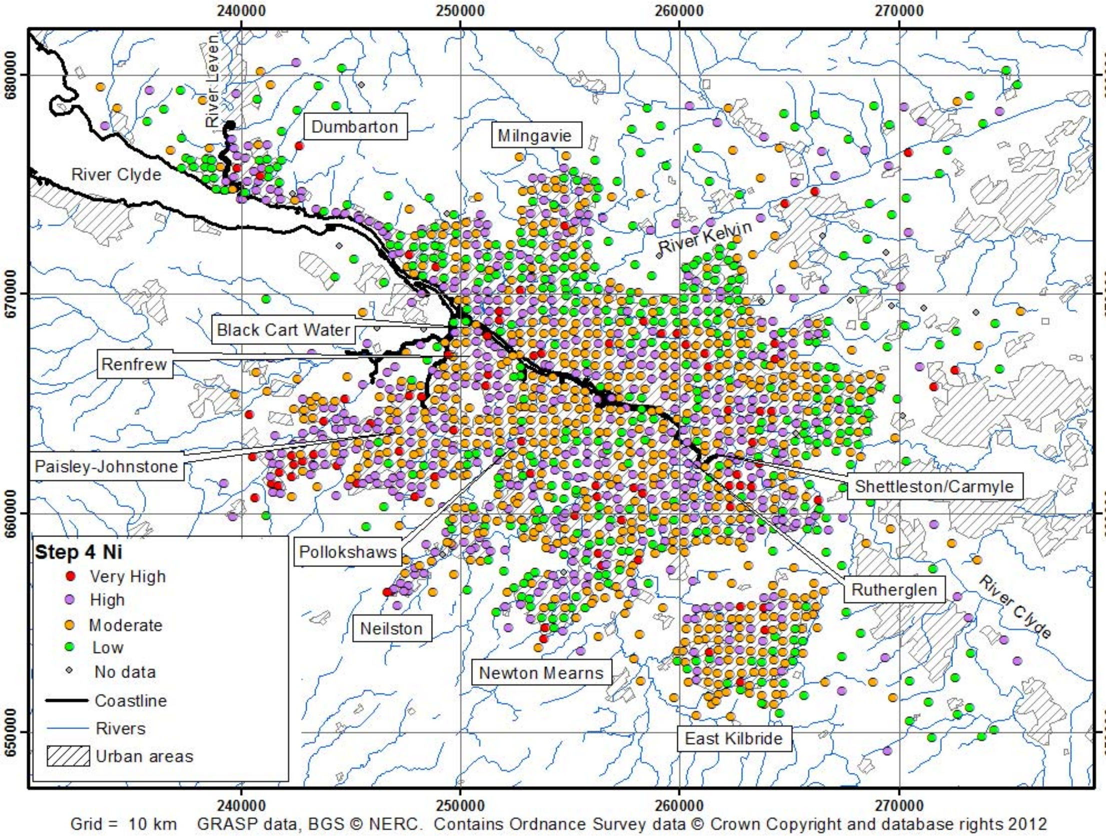
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012


Step 4 Fe
Very High
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
Neilston
Newton Mearns
East Kilbride
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012


Step 4 Mn
Very High
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
Neilston
Newton Mearns
East Kilbride
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012


240000
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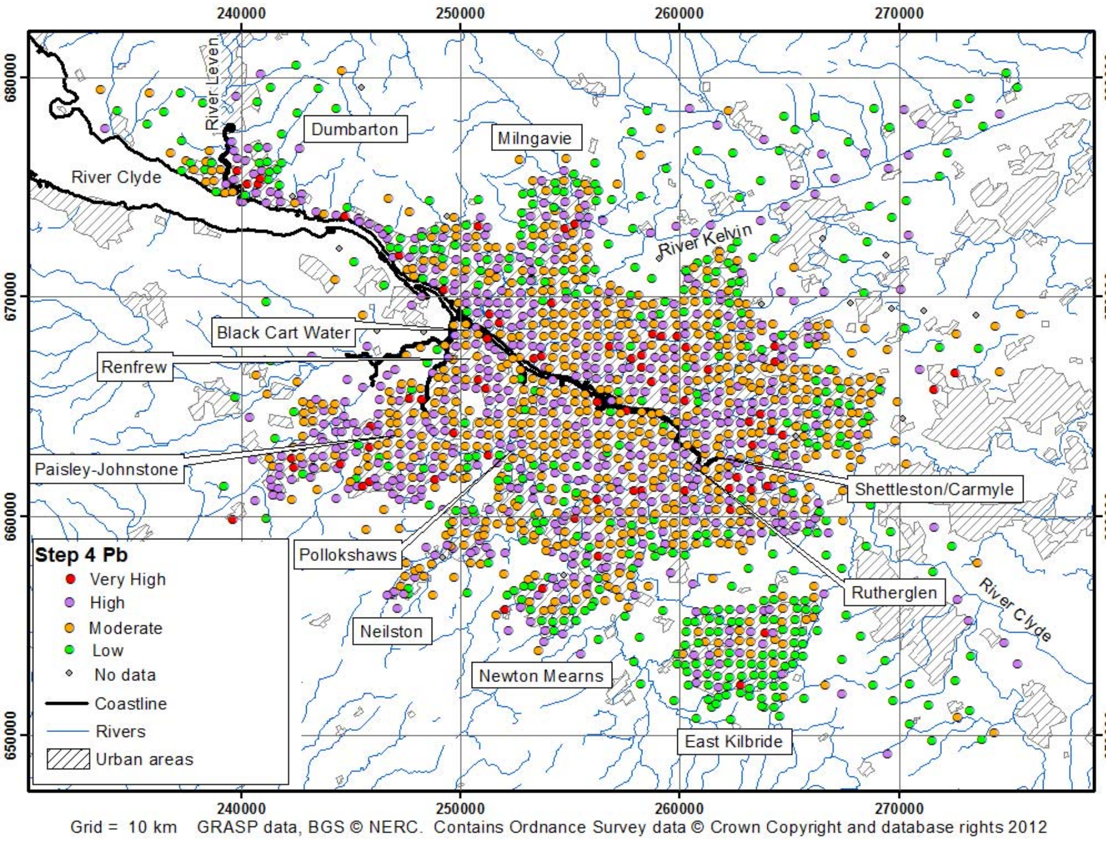
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
River Clyde
Neilston
Newton Mearns
East Kilbride
Step 4 Ni
Very High
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012


240000
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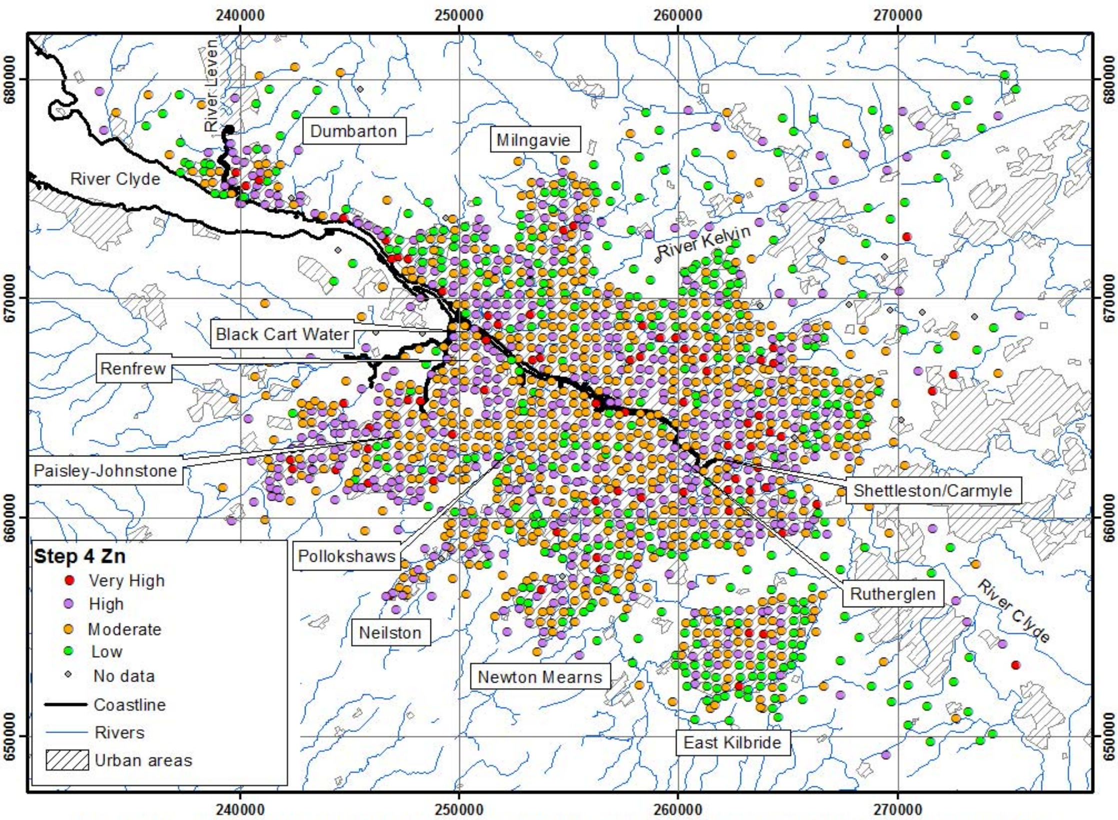
650000
River Leven
Dumbarton
Milngavie
River Clyde
River Kelvin
Black Cart Water
Renfrew
Paisley-Johnstone
Shettleston/Carmyle
Pollokshaws
Rutherglen
River Clyde
Neilston
Newton Mearns
East Kilbride
Step 4 Pb
Very High
High
Moderate
Low
No data
Coastline
Rivers
Urban areas
Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012



Grid = 10 km GRASP data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2012