



**British
Geological Survey**
NATURAL ENVIRONMENT RESEARCH COUNCIL

Clyde Gateway Pilot 3D Geological and Groundwater model

Responsive Surveys Scotland, Geology and Landscape Scotland
Commissioned Report CR/09/005

Clyde Gateway Pilot 3D Geological and Groundwater Model

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Keywords

Glasgow, bedrock modelling.

National Grid Reference

SW corner 255000,660000
Centre point 260000,665000
NE corner 265000,670000

Map

Sheet SC030E, SC031W,
1:50000 scale, Glasgow and
Airdrie

Bibliographical reference

MERRITT J.E., MONAGHAN,
A.A., LOUGHIN, S.C.,
MANSOUR, M.,
O'DOCHARTAIGH, B.E. AND
HUGHES, A.G. 2010. Clyde
Gateway Pilot 3D Geological and
Groundwater Model. *British
Geological Survey
Commissioned Report*,
CR/09/005. 94pp.

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) that describes the Pilot 3D geological and groundwater models for the Clyde Gateway and surrounding areas of eastern and southern parts of the Glasgow conurbation. The methods employed to produce the models, the uses and the limitations of the final products are described. The work was commissioned by a consortium comprising Clyde Gateway Developments Limited, Glasgow City Council, South Lanarkshire Council and Scottish Enterprise.

Acknowledgements

A large number of individuals from the Clyde Basin Urban Superproject (CUSP) have contributed indirectly to the project through their work in creating the platform on which the present project is based. Of the many individuals who have contributed, we would particularly like to thank the following:

Tony Irving, Bill McLean and Sandy Henderson for data entry and compilation, Gaud Pouliquen, for her earlier contribution to bedrock modelling, and Paul Williamson for technical review of an earlier model.

Dr Diarmad Campbell, who managed the project, and also manages the Clyde Urban Superproject, reviewed the report.

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Summary

This report describes the Clyde Gateway Pilot 3D geological model (superficial deposits, bedrock) and groundwater model (recharge and groundwater flow) which covers 1:10,000 scale Ordnance Survey sheets NS66SW, NS66NW and NS56SE. The groundwater model considers a broader area in general, and also, for practical purposes, a detailed consideration of NS56NE, based on available hydrogeological data. Therefore, the models, and report, address not only the Clyde Gateway area itself, but a larger area which includes for example the alignments of the M74 Extension and East End Regeneration Route.

The report provides background information to the model user including brief geological descriptions, model construction methods, uncertainty factors, limitations and a helpful 3D model user manual.

1 Introduction

The Clyde Gateway Pilot 3D geological and groundwater model is an interpretation of digital data held by the British Geological Survey published in an interactive 3D model viewing software package called the Subsurface Viewer. All geological surfaces and uncertainty rasters are also supplied as ArcGIS® layers. This report is designed to compliment the Subsurface Viewer model by helping the user understand how it was derived, providing brief geological explanations of modelled units, clarifying model limitations and supplying a simple user manual.

1.1.1 Model volume

The superficial deposits and bedrock model (Figures 1a, b) coordinates are 260670, 265670, 255665, 260665, 255660, and 265660 covering 75 km² on the 1:10,000 map sheets NS66SW, NS66NW and NS56SE. The north-western coordinate of the groundwater model is 255670 and includes also map sheet NS56NE, covering 100 km².

The bedrock modelled surfaces extend to c.-650 m depth, with the largest faults projecting down to c. -1km.

The model covers key sites such as the Clyde Gateway regeneration area (mainly on NS66SW), the main sites for the 2014 Commonwealth Games, the Shawfield development site, the East End Regeneration Route and the M74 extension.

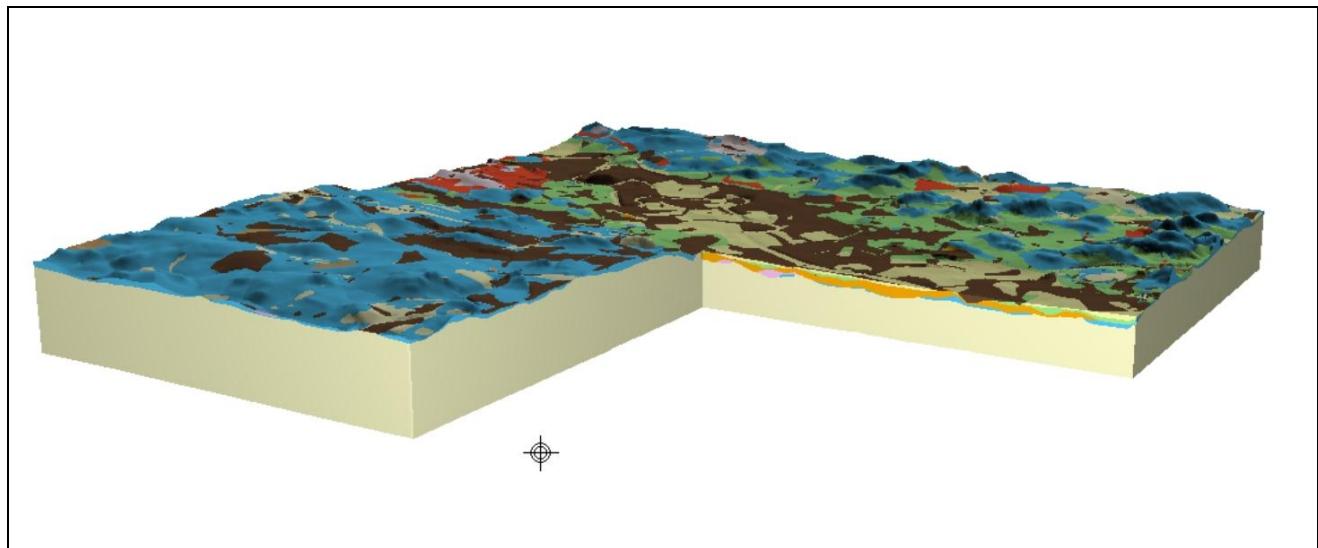


Figure 1a. Superficial deposits model, looking south east (vertical exaggeration x3).

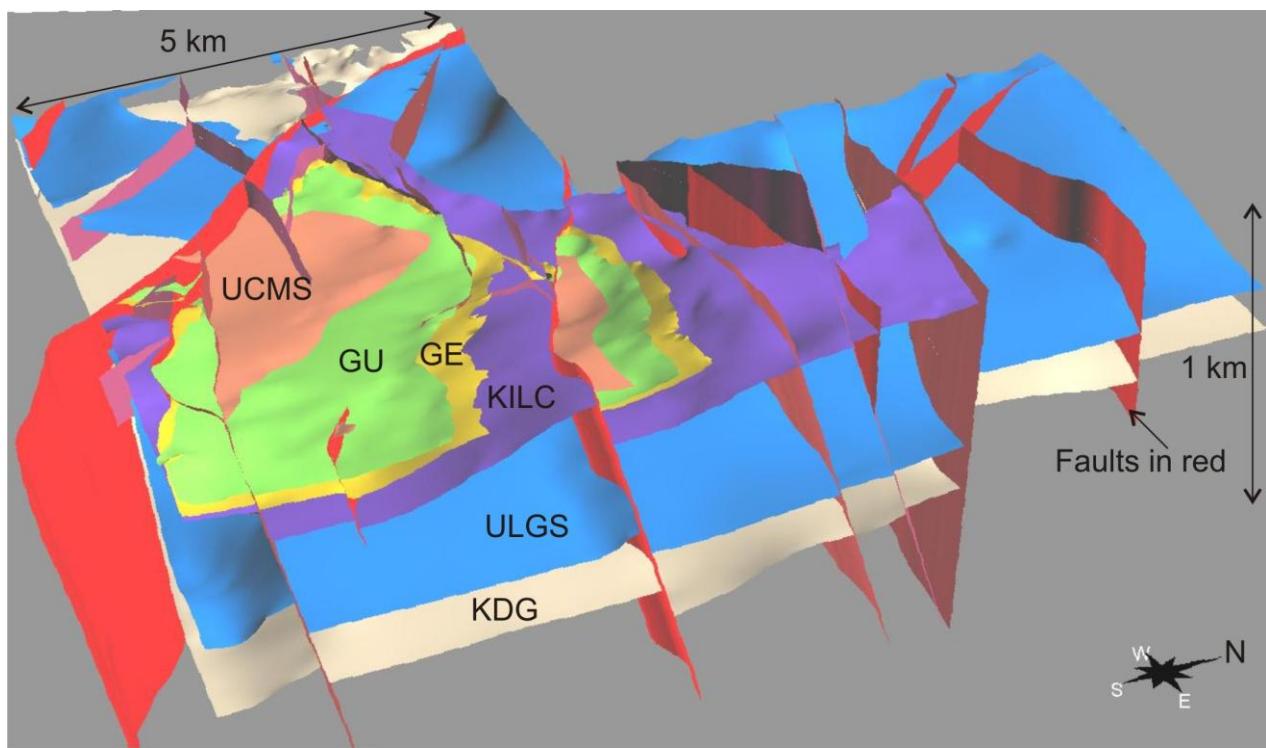


Figure 1b. Bedrock model, looking west (vertical exaggeration x3).

1.1.2 Modelled surfaces and faults

The modelled superficial deposits and bedrock surfaces in stratigraphic order are (Table 1):

| | |
|---------------------------------|---|
| MGR | Made Ground (made and worked ground undifferentiated) |
| P | Clippens Peat Formation |
| LAW | Law Sand and Gravel Member |
| GUF | Gourock Sand Member |
| KARN | Killearn Sand and Gravel Member |
| PAIS | Paisley Clay Member |
| BRON | Bridgeton Sand Member |
| ROSS_SAND | Ross Sand Member |
| ROSS_SZ | Ross Sand Member (silty sand) |
| BHSE | Broomhouse Sand and Gravel Member (sand and gravel) |
| BHSE_CLAY | Broomhouse Sand and Gravel Member (clay) |
| BHSE_SAND | Broomhouse Sand and Gravel Member (sand) |
| BILL | Bellshill Clay Member |
| WITI | Wilderness Till Formation |
| CADR | Cadder Sand and Gravel Formation |
| Rockhead unconformity | Combined base of all the superficial deposits |
| Base Upper Coal Measures (UCMS) | |
| Glasgow Upper coal (GU) | Worked coal in Scottish Middle Coal Measures Formation (MCMS) |

| | |
|--|---|
| Glasgow Ell Coal (GE) | Worked coal in Scottish Middle Coal Measures Formation (MCMS) |
| Kiltongue Coal (KILC) | Worked coal in Scottish Lower Coal Measures Formation (LCMS) |
| Knightswood Gas Coal (KDG) | Worked coal in Scottish Lower Coal Measures Formation (LCMS) |
| Base Upper Limestone Formation (ULGS) = Index Limestone (ILS) | |

Table 1. Summary of modelled surfaces

Table 2 below explains the main lithologies, origins and ages of the modelled Quaternary (superficial deposit) surfaces in the Clyde Gateway area.

| CLAY AND SILT | | SAND AND GRAVEL | | DIAMICTON | PEAT | LITHOLOGY |
|---------------|-----------|-----------------|------------|------------|----------|-----------|
| Marine | Lac/Fluv | Marine | Lac/Fluv | Glacial | Organic | ORIGIN |
| | | Gourock | Law | | Clippens | FLANDRIAN |
| | | Killearn | | | | |
| Paisley | | | | | | |
| | | Bridgeton | | | | |
| | Bellshill | | | | | |
| | | | Ross | | | |
| | | | Broomhouse | | | |
| | | | | Wilderness | | |
| | | | Cadder | | | DEVENSIAN |

Table 2. Summary of modelled Quaternary surfaces in Clyde Gateway area: lithology, origin and age (Lac – lacustrine, Fluv – fluvial).

Figure 2 illustrates the bedrock stratigraphy. GU and GE are the uppermost and extensively worked coals in the Scottish Middle Coal Measures Formation (MCMS). KILC is quite extensively worked in the Scottish Lower Coal Measures Formation (LCMS). KDG is extensively worked within the Limestone Coal Formation (Figure 2), cropping out on the western side of the area.

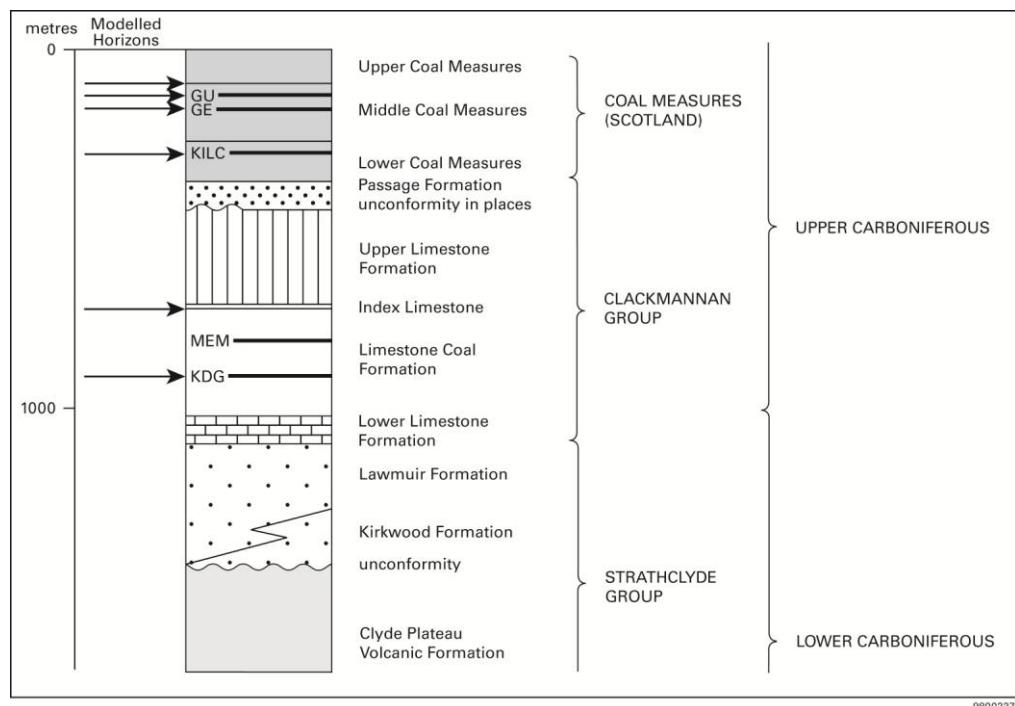


Figure 2. Summary bedrock stratigraphy of the modelled Carboniferous strata in the Clyde Gateway area. Coal name codes (e.g. GU) referred to in Table 1 above.

Thirty dipping faults were included in the bedrock component of the model (Figure 3). They were selected if they had throws of over 30 m or lengths of over 2 km, or were very important in constraining the mapped geological outcrop pattern.

Fault dips were calculated where data were available using the XYZ positions recorded in subsurface mining data linked to the surface outcrop position. The data were mainly available on NS66SW, showing that the majority had dips c. 60°. One fault, Burnside (Figure 3), has a c. 45° dip. Occasionally, fault information was encountered in boreholes. However, the amount of fault subsurface position information from mining and boreholes is generally very limited (and not enough to make a fault defining pointset). Thus, faults were created by projection from their mapped outcrop position at 60° (apart from Burnside at 45°).

The availability of mining information on NS66SW meant that faults could be analysed for their penetration at depth. Smaller faults were observed to terminate within 100 m of rockhead (e.g. F6, Figure 3) whereas larger structures (e.g. Rutherglen) penetrate the whole of the model. On NS66NW and NS56SE, mining information was more limited and faults incorporated in the model were generally larger in terms of length (and therefore probably depth also), such that faults on these sheets were extended to a standard depth of 1 km.

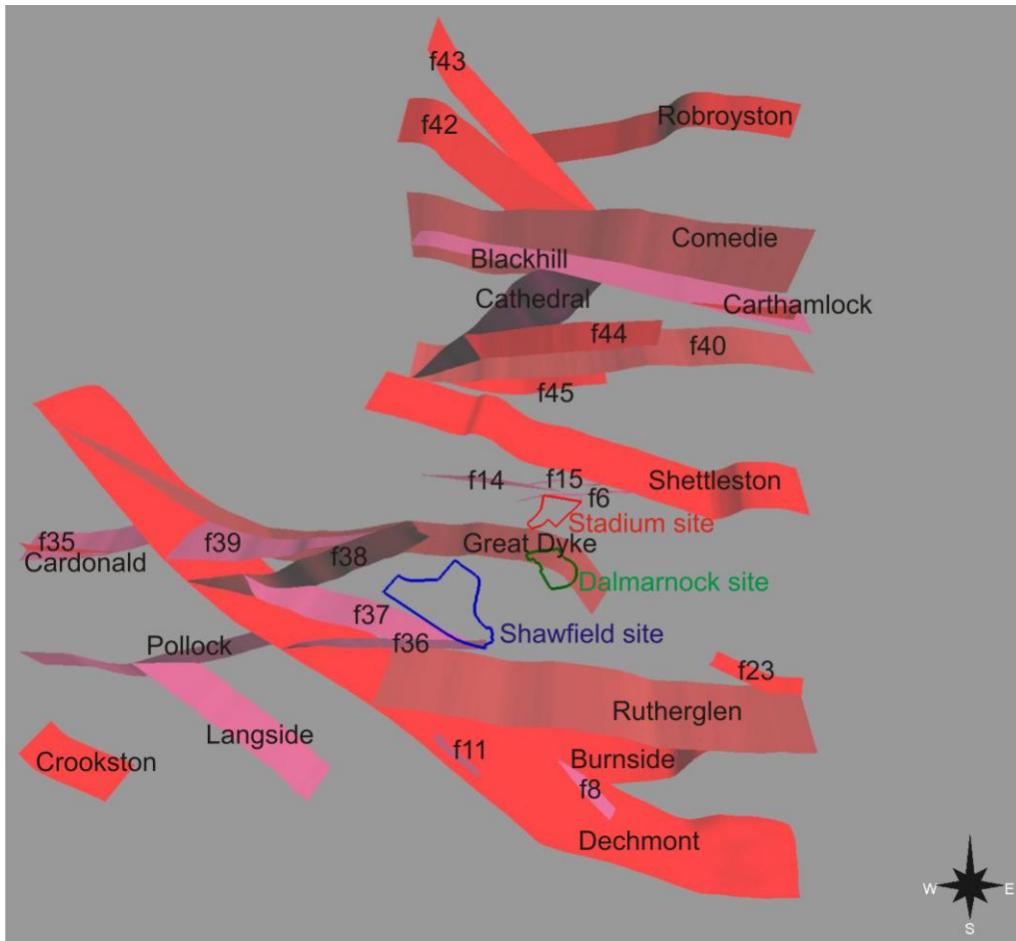


Figure 3. 3D faults included within the Clyde Gateway model, viewed from above. Where faults have been named, those names were used, otherwise faults were sequentially numbered. Three of the development sites are shown for geographical reference.

1.1.3 Summary of the bedrock geology

The bedrock geology beneath NS66SW, NS66NW and NS56SE comprises Upper Carboniferous Coal Measures and Clackmannan Group strata (Figure 2). The majority of the strata represent fluvio-deltaic to shallow marine facies consisting of argillaceous rock, sandstone, coal and limestone. The lithostratigraphy is primarily identified from interpretation of borehole records using the established BGS Carboniferous lithostratigraphic framework, lithostratigraphic and biostratigraphic markers (Browne et al., 1999; Hall et al., 1998; Figure 2).

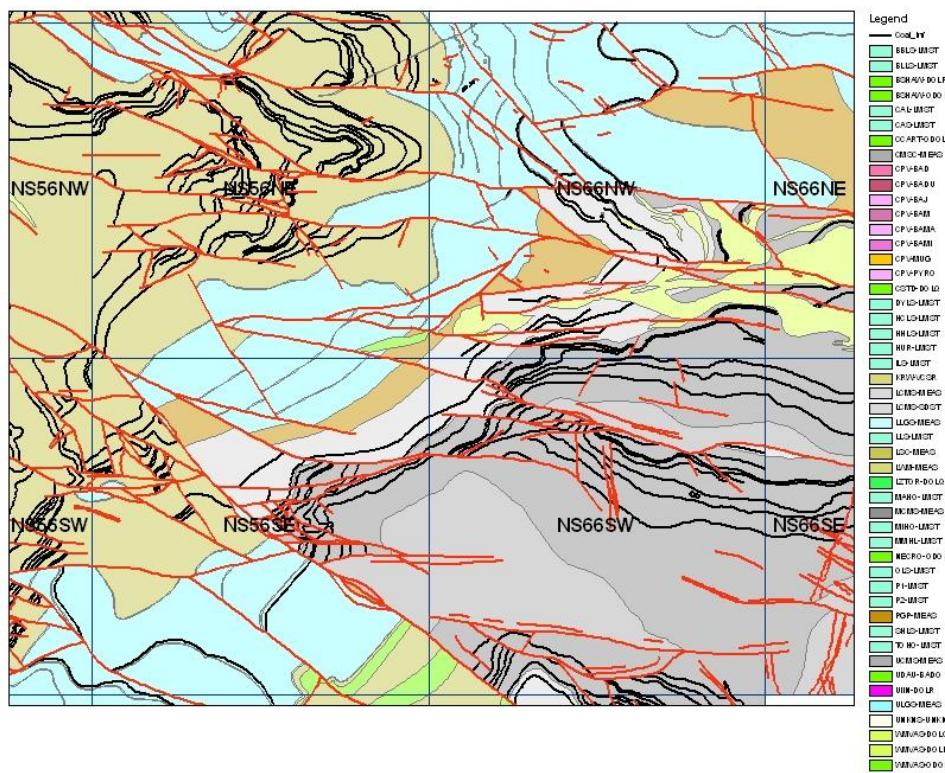


Figure 4. Bedrock map extracted from BGS DiGMap 10 k ©NERC, faults in red, coal seams in black, Coal Measures strata in grey, Upper Limestone Formation in pale blue, Limestone Coal Formation strata in beige on west of area. Igneous intrusions in green.

The sedimentary rocks are cut by Late Carboniferous igneous intrusive sills and they are faulted and folded. The most common larger faults are roughly E-W trending (e.g. Shettleston and Comedie, Figure 3). The Dechmont Fault is the major structure running through the area; it trends NW and downthrows Coal Measures to the NE against Clackmannan Group strata (Figures 3, 4). Fault patterns are complex, commonly either intersecting or tipping out within the modelled area.

Overall the geological structure is that of an easterly plunging, east-west striking open fold of Coal Measures rocks in the hangingwall of the Dechmont and Comedie faults. Clackmannan Group strata are folded into approximately NNE to NE-trending synclines and anticlines. All areas are cut by NW- to ENE-trending faults.

In terms of regional structure, the Dechmont Fault appears to form a deep and long-lived NW trending lineament. However, its throw (and therefore perhaps significance) does decrease to the NW of the studied area. It divides two Midland Valley Upper Carboniferous structural styles – NE trending half-graben/graben block and basin to the west (e.g. Ayrshire) and NNE trending growth folds to the east (e.g. Central Coalfield and Fife). Strike-slip to extensional tectonism is thought to have been active during the upper Carboniferous (Namurian-Westphalian), when the strata modelled here were deposited (Read 1988; Rippon et al., 1996; Underhill et al., in press), so stratal thickening and thinning across fault and fold structures is expected.

2 Superficial deposits GSI3D model

2.1 MODELLING WORKFLOW, USE AND LIMITATIONS

2.1.1 Workflow and compilation

The superficial deposits model was constructed in GSI3D using a NEXTMap® Digital Elevation Model (25m resolution), digital borehole data, 50 k digital maps, field slips and scanned cross-sections. Borehole data were entered to the BGS corporate database BGS Borehole Geology. Borehole entry and geological coding was checked by a geologist. The new AGS borehole data provided by the clients for the Clyde Gateway model was also digitally coded. The spread of borehole data across the area was variable, from extremely closely-spaced at site investigation locations to more widely spaced and isolated boreholes.

The methodology for construction of the model is described in great detail by Kessler et al. (2008; <http://nora.nerc.ac.uk/3737/1/OR08001.pdf>) but principally involves construction of cross-sections between the best quality borehole data followed by envelope construction around the limits of the geological units. GSI3D model calculation then uses the envelopes in combination with nodes on the geological surfaces along cross-sections to build geological surfaces by triangulation.

2.1.2 Scale

The model is most appropriate for use between scales of 1:10,000 and 1:50,000 in for example the assessment of potential infrastructure alignments and locations, and relatively broad scales of planning. However, the model is also well suited to act as a *guide* for site specific studies at more detailed scales, and especially as a basis for planning and improving the economic efficiency of, site investigations; however, the model should not be considered as a substitute for site investigations.

2.1.3 Limitations

- The model does not reflect the full complexity of the superficial geology. In reality, surfaces could have been subjected to more deformation in certain localities (e.g. 2.2.2).
- Best endeavours (quality checking procedures) were employed to minimise data entry errors but given the diversity and volume of data used, it is anticipated that occasional erroneous entries will still be present (e.g. boreholes locations, elevations etc.).
- To create ArcGIS® surfaces from the model, the TIN (triangular mesh) files have been converted to grids (rectangular mesh). A grid spacing of 10 m was used.
- The model is attributed with geotechnical and hydrogeological properties. These are bulk attributions based on point data in boreholes.

2.1.4 Uncertainty (confidence) layers

Theses are provided for each geological unit (superficial and bedrock) as overlays in the Subsurface Viewer model and as separate ArcGIS® layers. The colour code for the supplied layers is red for greatest uncertainty and green for lowest uncertainty (Figure 5).

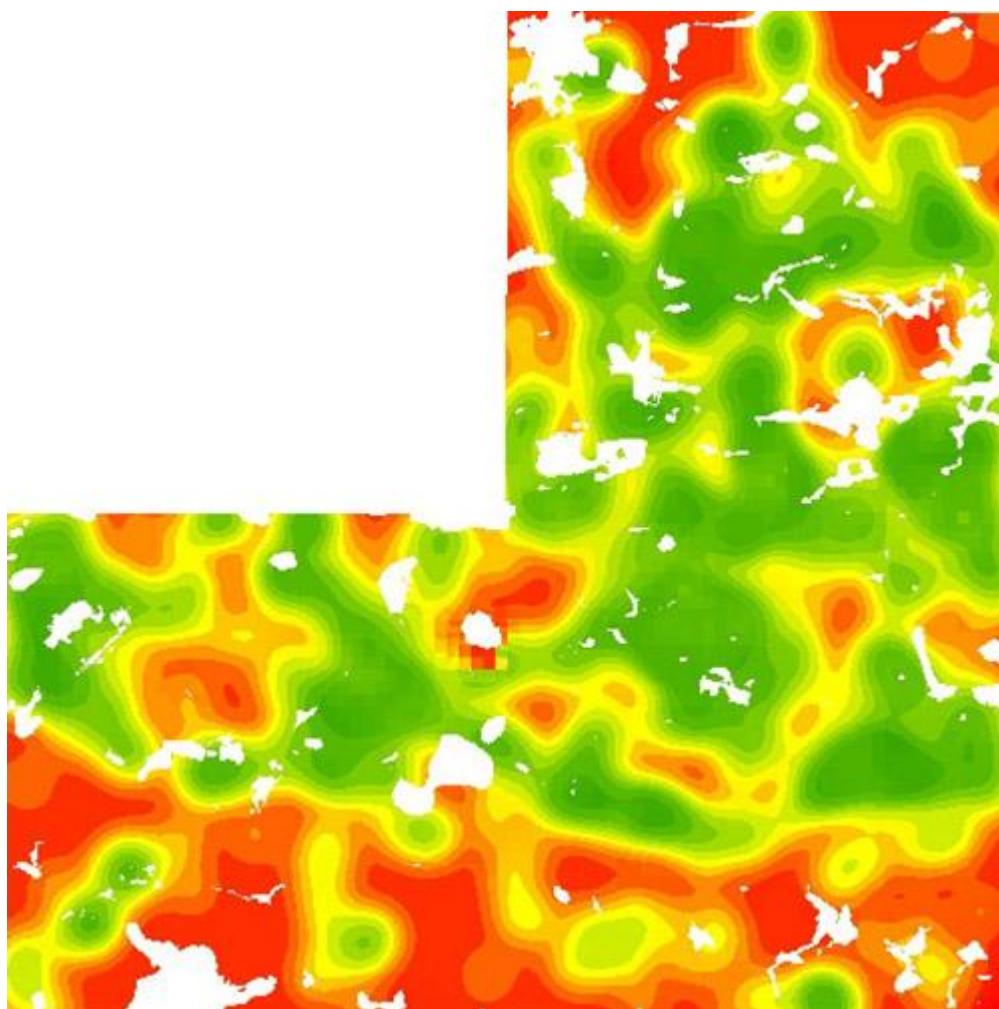


Figure 5. Uncertainty layer for WITI as supplied in the Subsurface Viewer

Uncertainty layers were calculated from a combination of data density and geological complexity of the modelled surface. The data density factor includes the distribution of borehole and map data. Note that all the data types were given the same confidence weighting. The software used (the in-house developed BGS confidence calculator v1.2) is not yet sophisticated enough to vary the error of the different data types. Un-interpreted data was not included in the calculation. A data density and geological complexity weighting, means the model will be most uncertain where there is little data and where the geological surface dip changes rapidly (coloured red on the uncertainty layers).

A majority of the available boreholes were directly consulted in the data selection process and the deepest, best-logged bores were used to construct the model. In total 1852 boreholes were specifically selected to construct the cross-sections on which the superficial model was based, out of a total of 13,000. In addition, however, many more boreholes not directly lying on specific cross-section alignments, were also considered during the construction of the cross-sections so that the overall construction of the model is based on an assessment of approximately 8000 boreholes. Uncertainty layers should be viewed individually with the relevant geological surface in the Subsurface Viewer.

Below (Figure 6) are some illustrations from the BGS confidence calculator v1.2. This is customised BGS software developed in Matlab to measure data density and geological complexity of an input Excel data file and ASCII modelled horizon grid. The output is a grid file ranked from *relative low* to *relative high* uncertainty.

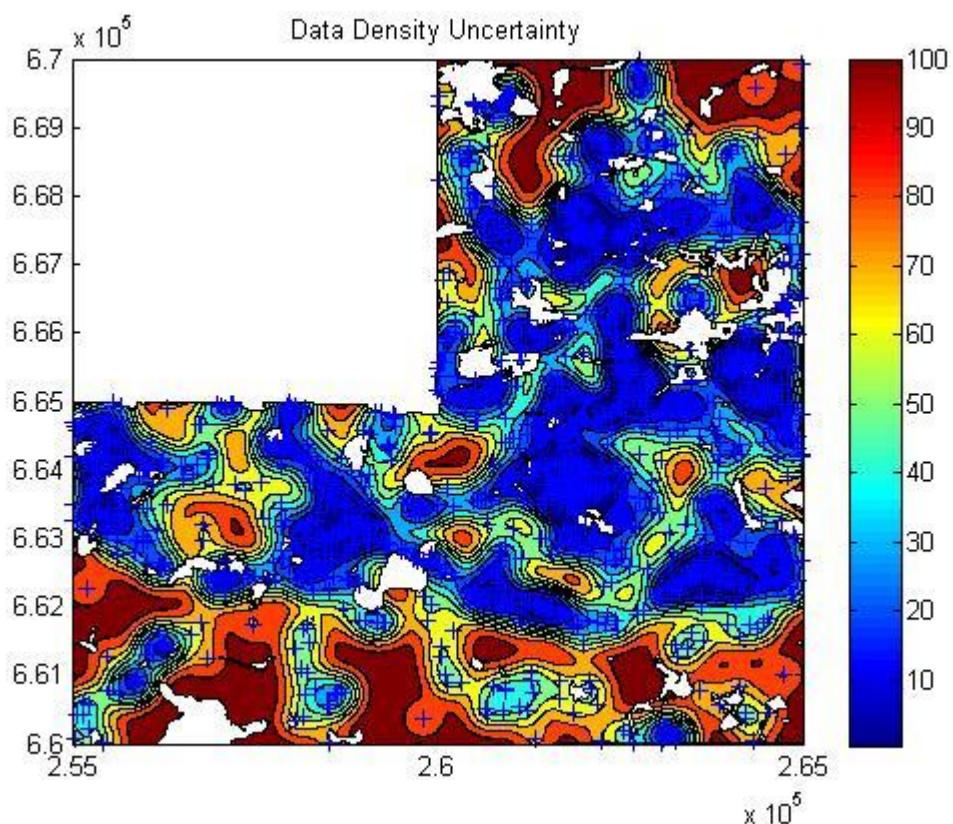


Figure 6. Example of data density uncertainty plot for WITI using an influence distance of 200 m. Data points are the blue crosses

An influence distance of 200 m and a scale of 0.5 -100 were used to calculate the data density uncertainty (e.g. Figure 6).

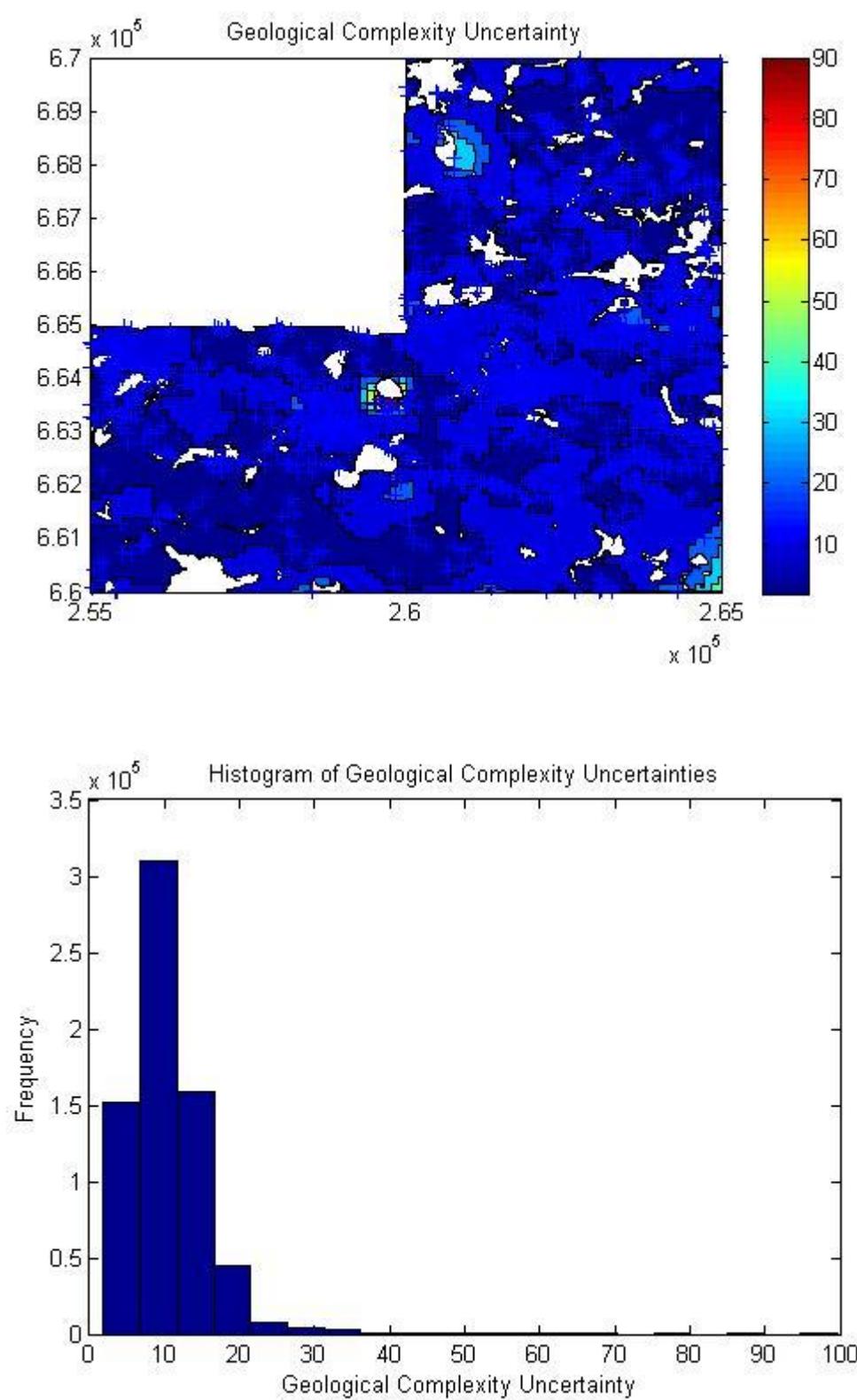


Figure 7. Example of geological complexity uncertainty for WITI

A grid of 100 by 100 with 500 iterations was used to calculate the geological complexity uncertainty (e.g. Figure 7).

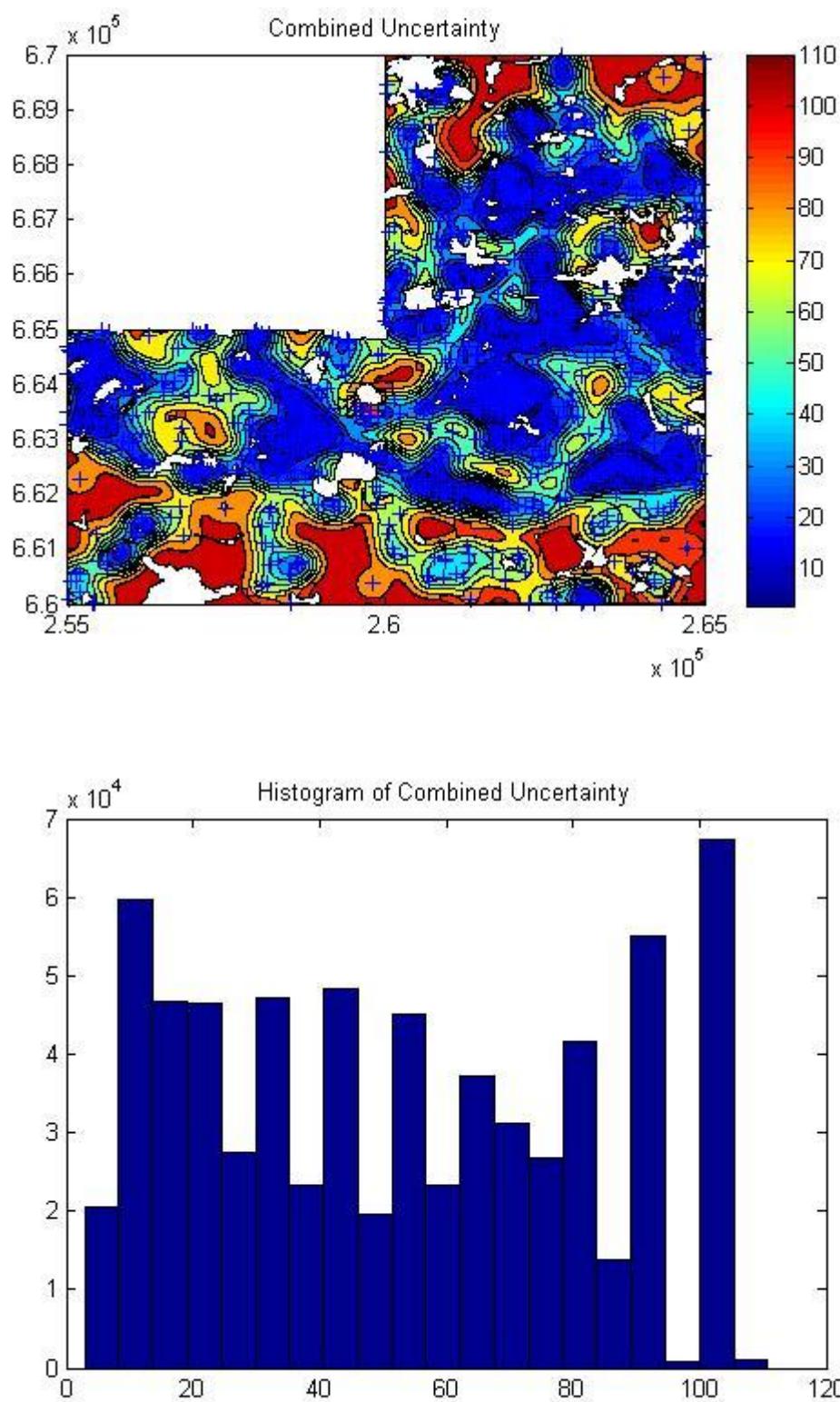


Figure 8. Example of combined uncertainty for WITI.

The relative, combined uncertainty scale (Figure 8) must be translated by the user into uncertainty categories, with the lowest number representing the lowest uncertainty and the highest number the highest uncertainty. For the Clyde Gateway model, 5 categories could be considered. In ArcGIS® this would be easy to achieve on the uncertainty raster grid by symbolising using 5 classes.

Lowest uncertainty (highest confidence) areas=1 would be those that are well constrained by geological data and where the geology is relatively simple. In these areas, the error on the model might be considered to be of the order of $\pm 10\text{m}$ in XYZ; for example, those areas of the WITI uncertainty surface on Figures X, Y, Z that are blue.

Average uncertainty (average confidence) areas = 3 would be those that are constrained by some geological data and where the geology is moderately complex i.e. faulted or folded. In these areas, the error on the model might be considered to be of the order of $\pm 30\text{m}$ in XYZ; for example those areas of the KILC uncertainty surface on Figures X, Y, Z that are green to turquoise.

Highest uncertainty (lowest confidence) areas = 5 would be areas that are not constrained by any geological data and where the geology is complex i.e. faulted or folded. In these areas, the error on the model might be considered to be of the order of $\pm 70\text{m}$ in XYZ. For example those areas of the WITI uncertainty surface on Figures X, Y and Z that are red to orange.

2.2 STRATIGRAPHY

The lithostratigraphy of the superficial deposits in the Glasgow area was formally described by Browne and McMillan (1989) and is summarised below, oldest first.

2.2.1 Cadder Sand and Gravel Formation

The Cadder Sand and Gravel Formation comprises bedded and trough cross-bedded, dense sand or silty-sand with gravel and some cobbles. It lies below the Wilderness Till, most commonly in bedrock depressions, and is thought to originate from outwash deposits, possibly fluvial or deltaic, formed in front of the advancing late Devensian ice sheet. The sands have yielded bones and teeth of woolly rhinoceros, from which Rolfe (1996) reported a radiocarbon age of 27.5 ^{14}C ka BP. Significant deformation of the upper parts of the unit has occurred due to overriding of the Late Devensian ice sheet.

2.2.2 Wilderness Till Formation

The Wilderness Till Formation is named after temporary sections seen in the Wilderness Plantation area north of Bishopbriggs. It is characterised by a diamicton comprising isolated boulders, gravel and pebbles in a sandy, silty to clayey matrix (Browne and McMillan, 1989).

The distribution of the till is shown in Figure 9. It forms the characteristic drumlinised terrain of many parts of the Clyde Valley. The till is thickest and crops at surface on high ground (up to 75 m OD) to the north and south of the Clyde valley. On the north side of the valley, a partially buried east-west oriented ridge of diamicton (drumlin) is over 20 m thick. Two discrete diamicton units separated by sand and gravel are shown in some borehole records (especially in the north-east part of the map). This may simply represent a lens of sand and gravel in the Wilderness Till, or there may be an older till present. Alternatively, there may be repetition of the Wilderness Till by glaciectonic thrusting.



Figure 9. Extent of the Wilderness Till Formation (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

2.2.3 Bellshill Clay Member

The Bellshill Clay Member occurs in the southern central part of sheet NS66SW. It comprises glaciolacustrine silty-clay with wisps, laminae and bands of silt and sometimes sand.

2.2.4 Broomhouse Sand and Gravel, Clay, and Sand members

The Broomhouse Sand and Gravel is named after the Broomhouse area of eastern Glasgow where it most commonly overlies the Wilderness Till Formation. It comprises glaciofluvial ice-contact deposits, which produce features such as esker ridges, mounds, isolated flat-topped kames and kettleholes. Overall, the most abundant deposit is sand, except in esker ridges where gravel dominates. Sands are planar and trough cross-bedded, ripple laminated and horizontally laminated, gravels are typically massive or crudely bedded. Deposits are up to 25 m thick and flow directions were towards the east (Browne and MacMillan, 1989).

In the Clyde Gateway model the deposits are located to the north of the present Clyde valley implying that the valley axis has moved to the south since the Late Devensian. The deposits are typically west-north-west–east-south-east aligned (Figure 10) and tend to thicken and dip towards the east, implying eastward drainage.

In the north-east quadrant of the map, where the Wilderness Till is thin to absent, thin clays are locally present under the sand and gravel of the Broomhouse Sand and Gravel Formation. These clays have been correlated as Broomhouse Clay. A sand deposit, the Broomhouse Sand is also present in places.

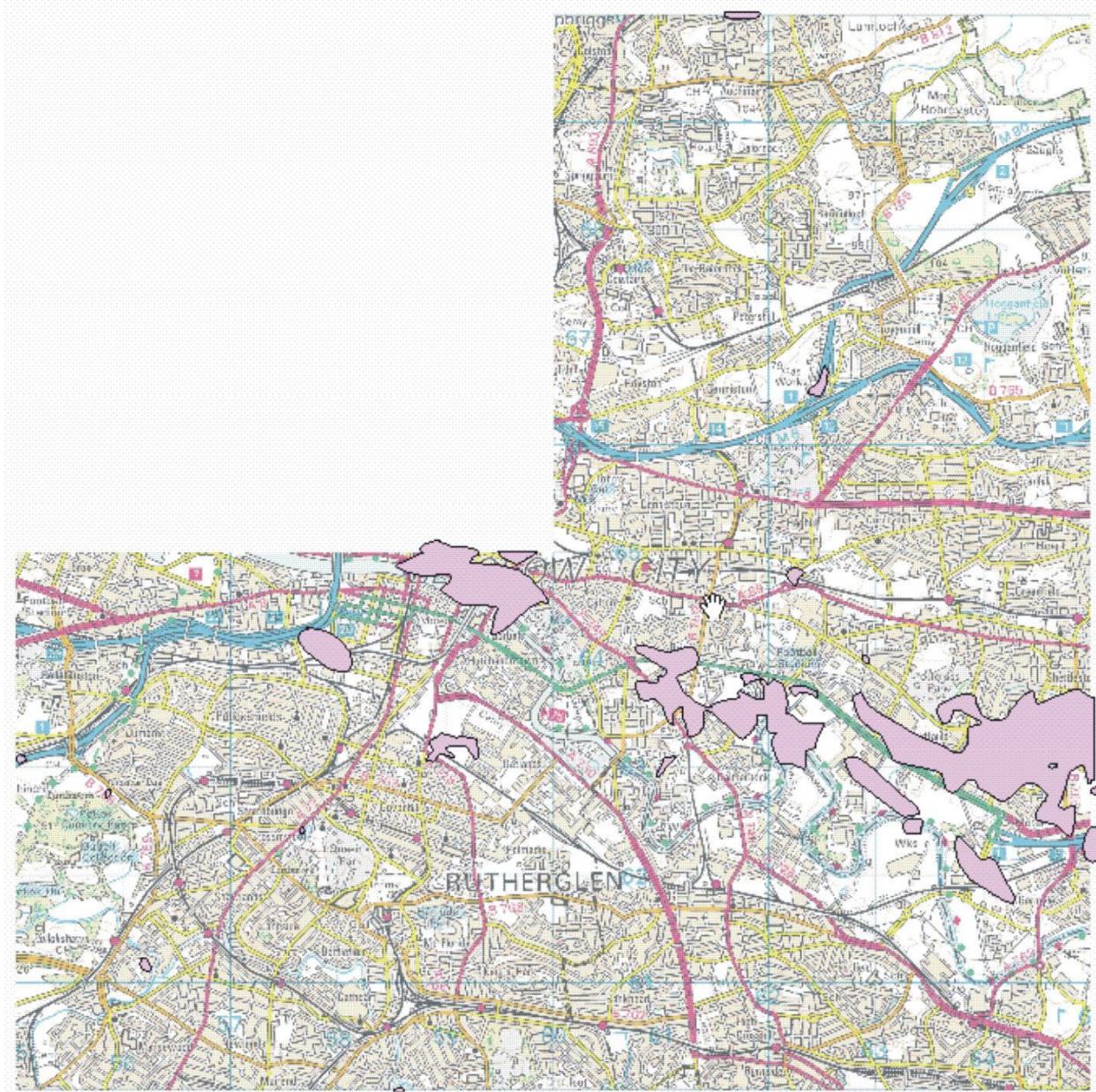


Figure 10. Extent of the Broomhouse Sand and Gravel Member (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

2.2.5 Ross Sand and Ross Silty Sand Members

The extent of the Ross Sand Member is shown in Figure 11. It is exposed at surface as an east–west aligned sandy ridge. The main lithology is sand or sand and silt. At the base there are clays and locally there are thin gravel layers. The deposits are glacio-lacustrine in origin, Browne and MacMillan (1989).

For modelling purposes, we have separated the different lithologies into two units. Massive sand (Ross_s) forms the main unit and sand with silt is the second unit (Ross_sz). The massive sand deposits occupy a deep palaeo-valley on the east side of the area.

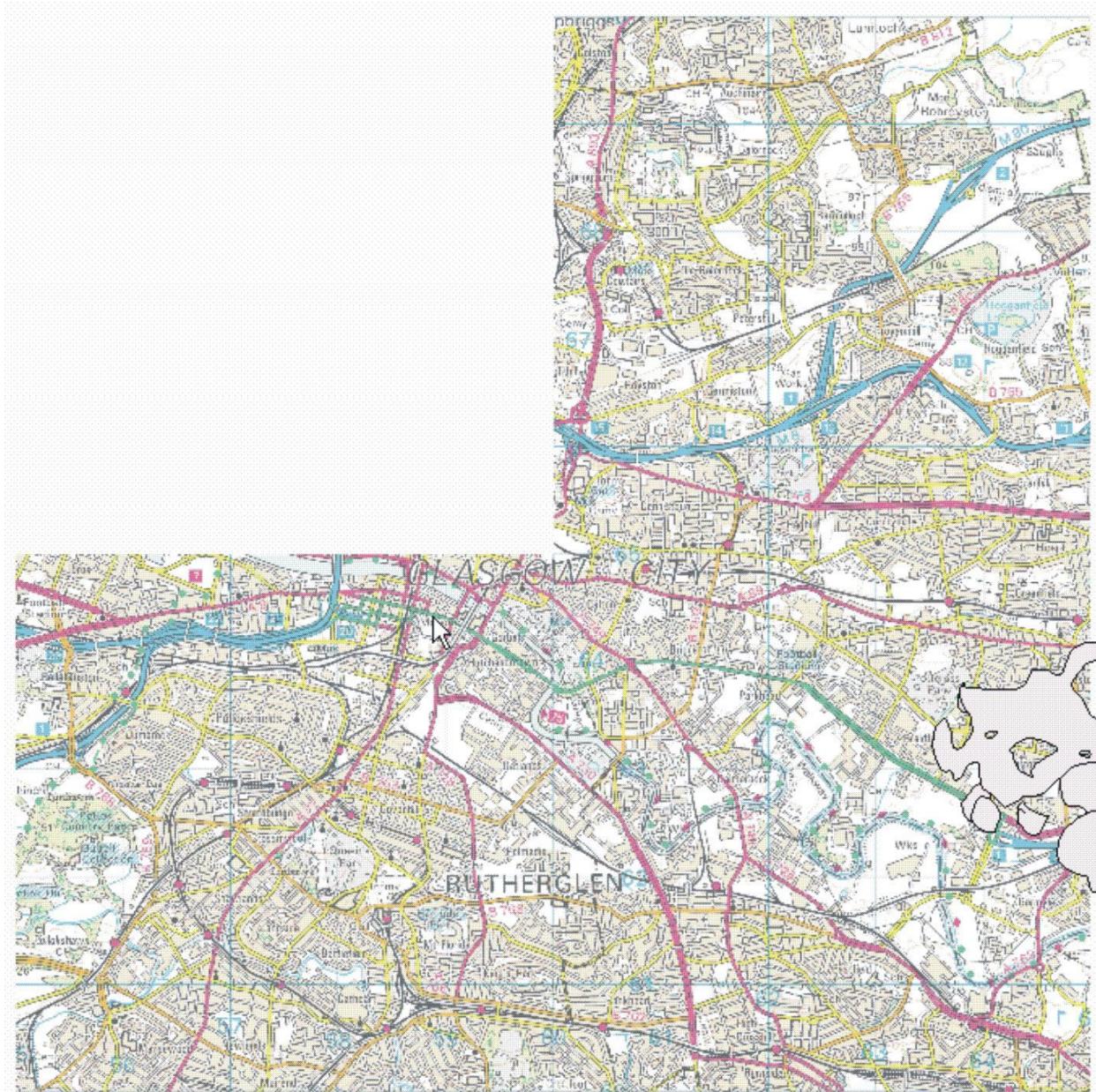


Figure 11. Extent of Ross Sand and Ross Silty-sand Members (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

2.2.6 Bridgeton Sand Member

The Bridgeton Sand Member is characterised by fine to medium, massive sand; locally fine to coarse gravel and boulders occur in a sandy matrix. There is some flat bedding but generally the deposits are massive. Deposition was by westward flowing floodwater. Browne and MacMillan (1989) suggested that deposition was on submarine outwash fans following catastrophic draining of Lake Clydesdale.

The deposit fills a buried valley in the north western part of the study area (Figure 12). The palaeo-valley runs roughly to the west-north-west–east-south-east and slopes north westwards. The morphology supports its origin as a subaqueous outwash deposit emplaced by westward flowing floodwater.

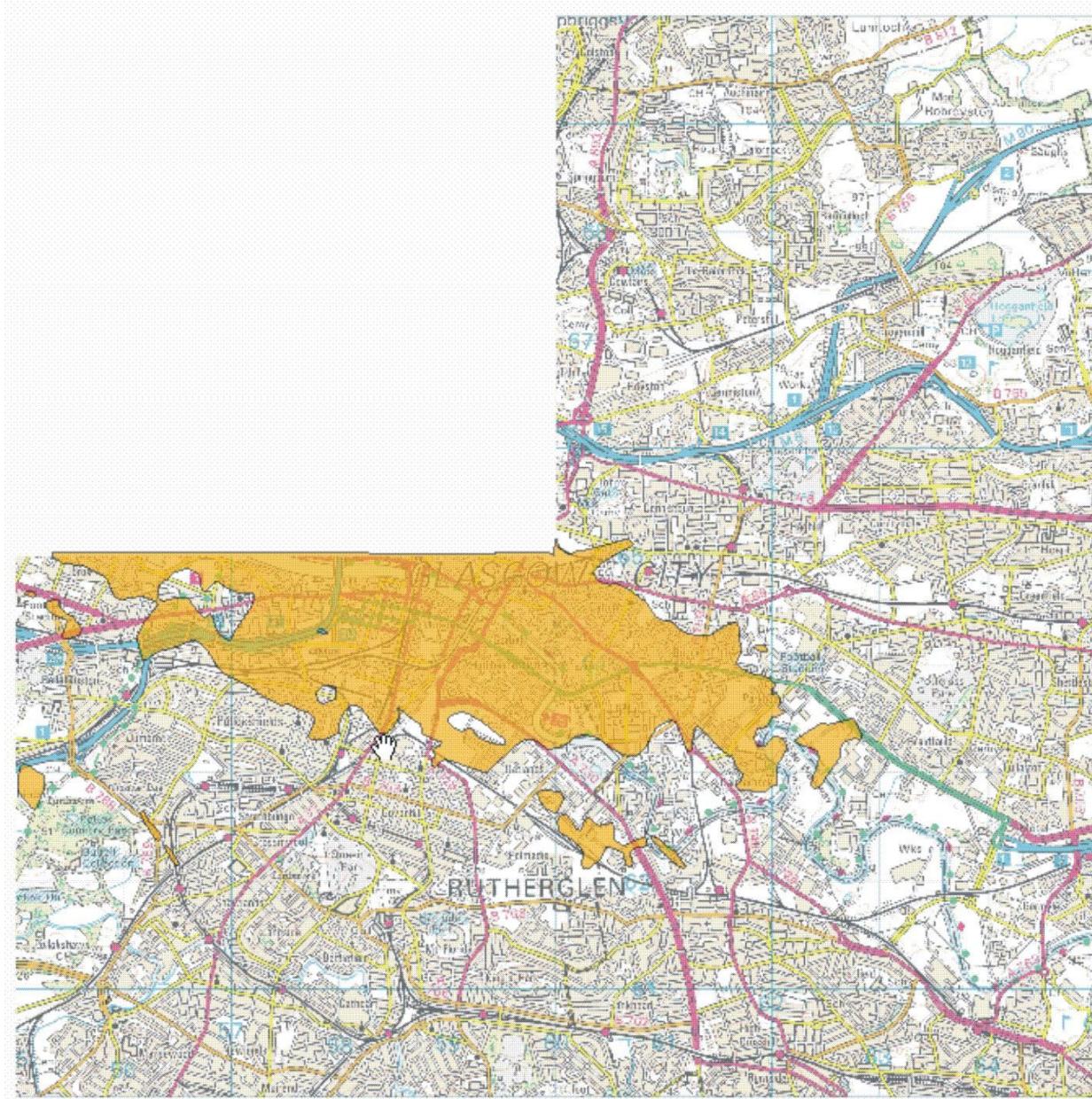


Figure 12. Extent of Bridgeton Sand Member (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

2.2.7 Paisley Clay Member

The Paisley Clay Member comprises layered clays and silts deposited in a glaciomarine setting. The retreating glaciers were believed to be to the northwest, in the sea lochs of the Southern Highlands. Relative sea level was high when deposition of the Paisley Clay Member commenced and some clays were deposited at elevations up to 40 m above OD (Browne and McMillan, 1989). The deposit is a widespread, distinctive clay and silt unit which is easily recognised in the boreholes used in modelling. Its distribution is shown in Figure 13.



Figure 13. Extent of Paisley Clay Member (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

2.2.8 Killearn Sand and Gravel Member

The Killearn Sand and Gravel Member comprises mainly sand with some clay layers and some gravel. It does not occur above 40m OD (Browne and McMillan, 1989) and may include beach, river terrace and delta deposits. Its distribution is shown in Figure 14.

All sand or sand and gravel units that crop out above the Clyde valley floor and stratigraphically above clays and silts of the Paisley Clay Member were assigned to the Killearn Sand and Gravel Member. The full extent is uncertain but it appears to be well developed in the north-east quarter of sheet NS66SW where the Paisley Clay Member is poorly developed or not present. Boreholes show varied assemblages of sand and gravel, sand and thin silt/clay layers and as a result, it is very difficult to distinguish between the Broomhouse, Bridgeton and Killearn Formations.

On the south side of the Clyde valley, the Killearn Formation forms four separate terraces each at an altitude of 35-40 m. These may be beach deposits or river terraces, whereas the large deposit in the north east of the sheet was deltaic with a northerly or north-easterly source.



Figure 14. Extent of Killearn Sand and Gravel Member (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

2.2.9 Gourock Sand Member

The Gourock Sand Member is characterised by fine to coarse sand with some silt, clay and locally gravel. Deposition was in an estuarine environment with fluvial processes dominating in the east of the Clyde valley and a fully marine environment in the west (Browne and McMillan, 1989). The extent of the Gourock Sand Member is shown in Figure 15.

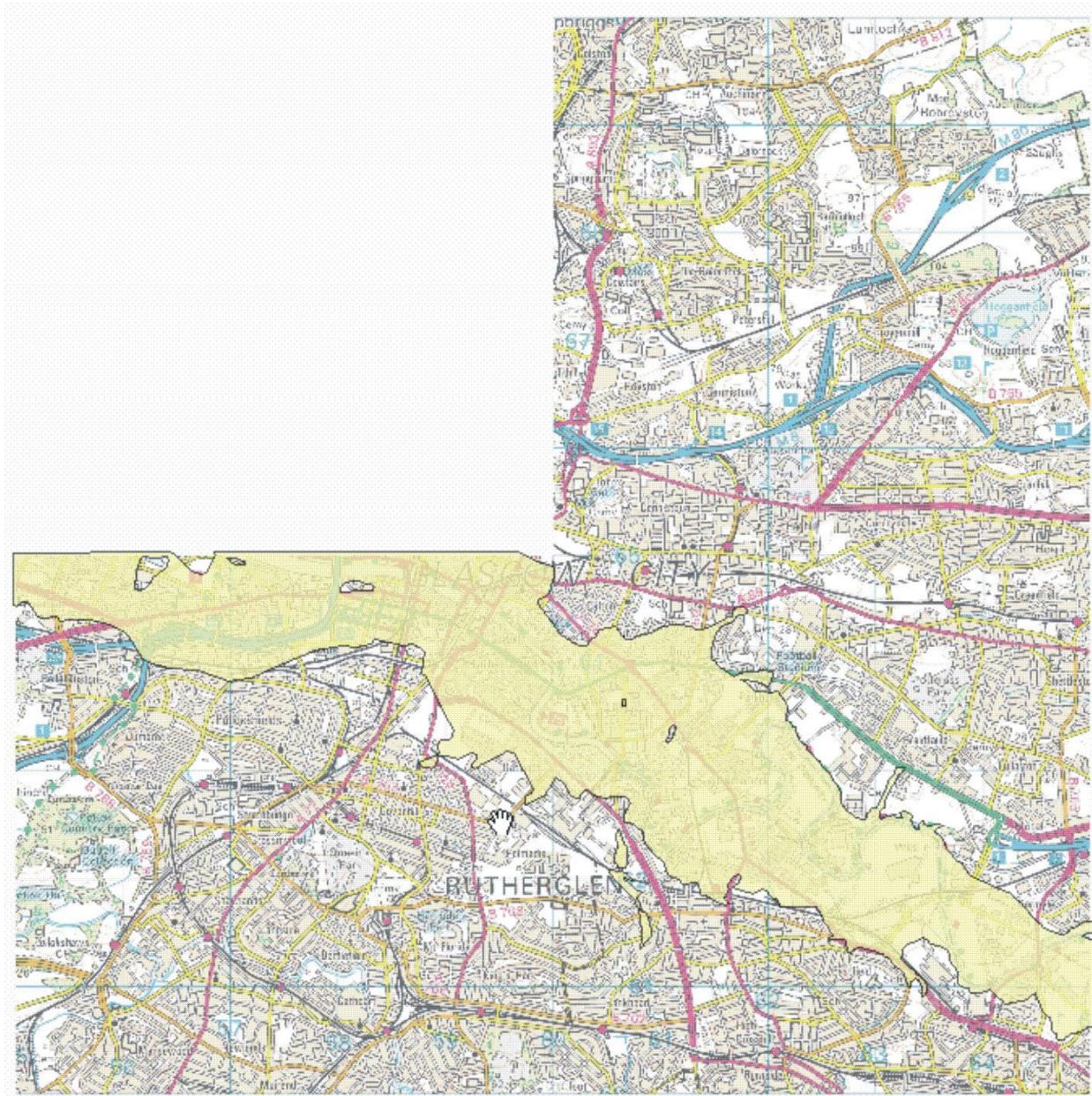


Figure 15. Extent of Gourock Sand Member (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

2.2.10 Law Sand and Gravel Member

The Law Sand and Gravel Member comprises fine to coarse sand with some silt and fine gravel. The Law Formation also includes recent (currently accumulating) river deposits in the Clyde valley. In the superficial deposits model, only the recent alluvium found in the tributaries to the Clyde valley have been assigned to this member.

2.2.11 Clippens Peat Formation

The Linwood Borehole (Browne and McMillan. 1989) contains the typical section of the Clippens Peat Formation. Below 45 cm of very peaty stony soil there was 1.3 m of peat, resting on 5 cm of grey rooty clay, followed by a further 84 cm of peat to the base of the formation at 2.64 m depth. The base of the upper bed of peat was at 8.43 m OD and the base of the lower at 7.54 m OD. The basal 3 cm of each peat bed have been radiocarbon dated to 7110 ± 50 years BP for the base of the upper peat and 9540 ± 50 years BP for the base of the lower. A single specimen of the marine gastropod *Onoba semicostata* was found in the clay bed, tentatively indicating a

marine origin, the transgression ending earlier than 7100 years ago. Reliable indicators of saltmarsh vegetation are not found in the peat record but ericaceous pollen taxa may indicate the development of a coastal heath. The formation was originally defined as found only in the Linwood area but now includes all late Devensian and Holocene peats in the Clyde Catchment.

2.2.12 Made Ground

Made ground in the 3D model represents a combination of made and worked ground including filled and partially back-filled pits and quarries. Hence it comprises all anthropogenic deposits. Made ground has not been subdivided as this would require a very detailed, and time-consuming, interpretation of all the borehole data along with air photos and field slips. In making the model, there was only time to use a representation of the available data. An accurate 5 m DTM and good quality borehole descriptions would be essential to the proper detailed modelling of the made ground in the Clyde Valley area and subdivision of the made ground should be considered in future models.

3 Bedrock 3D model

3.1 DATA ENTRY AND COMPIRATION

The bedrock model was constructed from borehole, mine plan, map outcrop and interpreted data.

3.1.1 Borehole data

Borehole data were entered to the BGS corporate database BGS Borehole Geology. Borehole entry and geological coding was checked by a geologist. The new borehole data provided by Glasgow City Council and partners for the Clyde Gateway model resulted in >20 new data points for the GE and GU coals, a few new data points for the base UCMS and no new data for KILC, base ULGS and KDG surfaces.

The spread of borehole data across the area was very variable (Figure 16), from closely-spaced site investigations, occasionally with multiple data entry points, to in extreme cases, boreholes more than a kilometre apart. Data points were inevitably concentrated around the outcrop of worked coals and were sparse on stratigraphic surfaces in deeper parts of the basin.

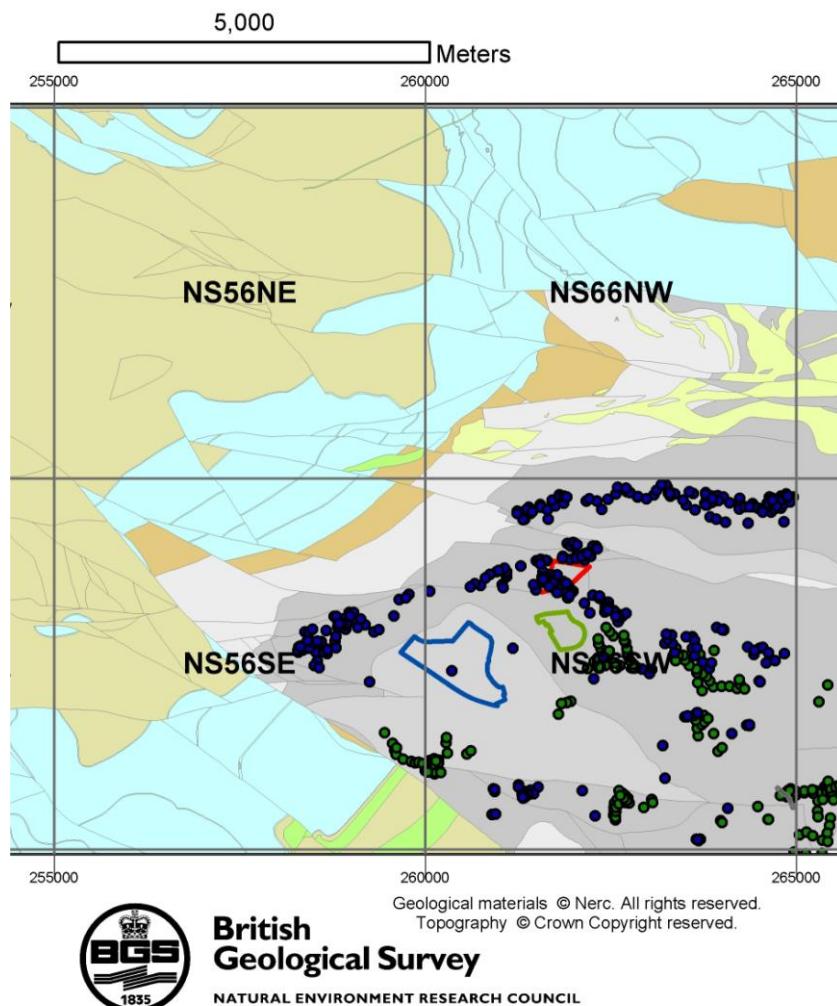


Figure 16. Distribution of borehole data points on the Glasgow Ell Coal in blue and mining data points on the Glasgow Ell Coal in green. Sites shown as on Figure 3

Most borehole data points have a reasonably good level of certainty. Boreholes with very poor quality records or very poorly known sites were not coded into the database. However, there can be uncertainty in geologically coding short, isolated site investigation boreholes, in a driller's record of a borehole (i.e. if not geologist examined) or sometimes in the siting of the borehole. However, these should result in errors in location being no greater than about 5–10 m in Z, and perhaps 20–50 m in terms of XY.

3.1.2 Mining data

Mining data were compiled from all available abandonment plans. These consist of spot heights surveyed on the base of worked coal seams underground, and rarely of structure contour elevation data. Many of the older workings had no spot height elevation data. The distribution of mining data points is variable. These data points have a high confidence level as they were systematically surveyed in. Estimates of error on mining data points range from 0–5 m in Z and 0–25 m in XY.

The mining dataset also provided valuable data on subsurface faulting and therefore on dips of faults.

3.1.3 Map data

The bedrock map represents the outcrop (or subcrop) of stratigraphic horizons at rockhead i.e. very commonly buried beneath superficial deposits. Exposed outcrop of bedrock is rare. 1:10,000 scale digital map data were used in the bedrock model in several different ways:

1. Coal seam outcrop and base unit boundaries formed important point sets to constrain the model outcrop.
2. Outcrop polygons were created to form the outline curve which bounds the area covered by each geological surface.
3. The fault traces at outcrop to be modelled were selected from the map and loaded to GOCAD™.

The map data for NS66SW had been revised prior to this study and an updated map published (BGS, 2008). The map data for NS56SE and NS66NW were revised prior to the study but those revisions have not been published i.e. the model contains more up-to-date map linework than does the current edition of the 1:10,000-scale maps (BGS, 1995, 1996).

The errors in mapped outcrop line work are extremely variable – from 0–10 m in XYZ where seen at outcrop, to tens of metres where an interpretive outcrop was created from little constraining data.

3.1.4 Interpreted geological data

Expert geological interpretation added during modelling falls into three categories: firstly, two cross-section interpretations on NS66SW; secondly scattered interpreted data points; and thirdly, interpretations of fault-surface contacts and removal of overlaps during modelling in GOCAD™. The first two datasets are kept as interpreted data in a data file; the latter is geological knowledge that was incorporated in the model during the modelling process.

3.1.5 Existing bedrock models

The Clyde Gateway model builds on previous preliminary BGS models of eastern Glasgow, such as that licensed to Glasgow City Council in 2005.

3.2 GOCAD™ MODELLING WORKFLOW

GOCAD™ is a 3D modelling software package used extensively in the hydrocarbons industry. A standard BGS GOCAD™ modelling workflow using version 2.1.6 structural workflow was employed. GOCAD™ calculates triangulated mesh based on XYZ data points and then the geologist modeller undertakes various processes to aid geological interpretation in data poor areas. The workflow steps comprise:

- Data collation/extraction from databases for horizons, faults, DTM/bathymetry
- Loading data to GOCAD™, data cleaning, merging different data types, apply Z from DTM to bedrock linework
- Prepare data resources for inclusion in the GOCAD™ Structural Modelling Workflow (SMW).
- Application of the GOCAD™ SMW, comprising:
 - Data Management
 - Volume of Interest Definition
 - Fault Modelling
 - Horizon Modelling
 - Fault Contact Modelling

- Horizon-Fault Contact Modelling
- Obtain additional geological information including expert advice to better constrain the model in these areas.
- Post-SMW enhancement, comprising multiple manual iterations of:
 - Identify irregularities: visual inspection etc to highlight areas where surfaces differ from the conceptual geological model.
 - Horizon modification/interpretation by removal of crossovers, hand-editing of fault-horizon contacts
- Checking and approval

Once finalised, checked and approved, the bedrock model was exported to GSI3D for loading into the subsurface viewer and to ArcGIS® 9.2 as raster grids.

3.3 RESULTS OF THE BEDROCK MODELLING

3.3.1 Overall geological structure

The fault structure is dominated by major approximately east–west trending faults such as the Comedie and Rutherglen faults (Figure 3), and northwest trending structures, the largest of which is the Dechmont Fault (Figure 17).

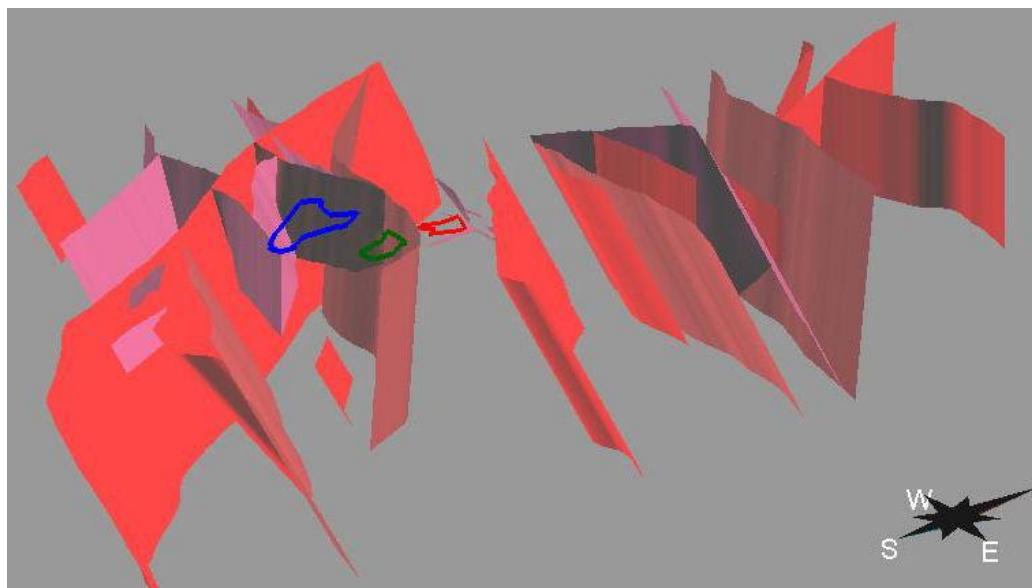


Figure 17. Modelled fault network over the Clyde Gateway area, looking west

The upper three surfaces of the East End Glasgow model (base UCMS, GE and GU) show a roughly east–west trending synclinal structure bounded by the Burnside, Dechmont and Great Dyke faults at the western end (Figure 1b). The structure is dissected by, and repeated in, the hangingwall of the Shettleston Fault. The GE reaches a maximum depth of c. –200 m in the model.

Because of their greater lateral extent, more complex structure can be seen in the lower three modelled surfaces KILC, ILS and KDG (Figure 18). The structure is essentially one of overall easterly dipping strata that have undergone gentle folding and are cut by easterly and northwesterly faults with throws up to c. 300 m (Figure 1b, 18). The base KDG reaches a maximum depth of c.–750 m in the hangingwall of the Shettleston Fault.

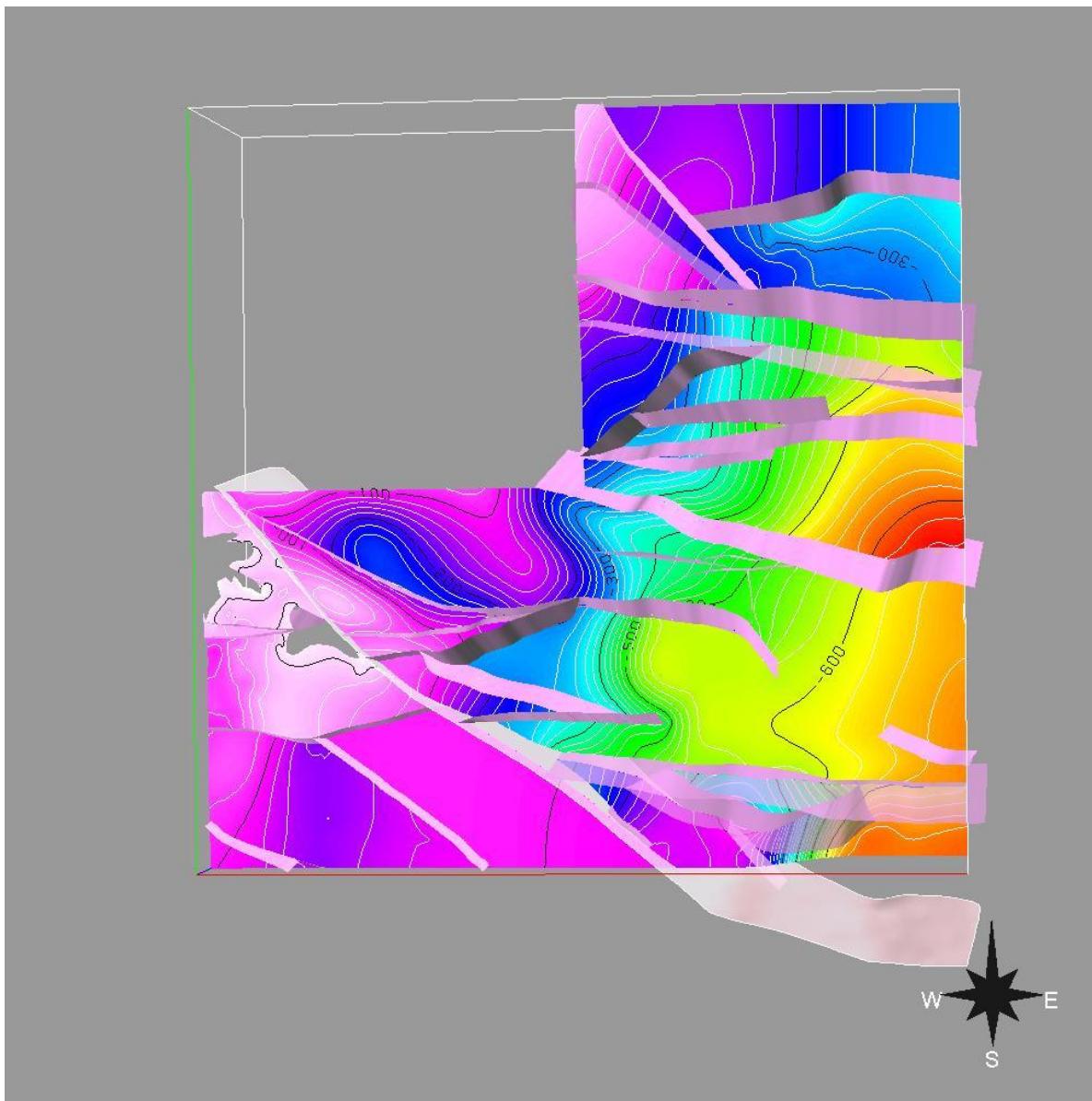


Figure 18. Contours shaded on the base KDG modelled surface looking from above

3.4 MODEL USE AND LIMITATIONS

3.4.1 Scale

The model is most appropriate for use between scales of between 1:10,000 and 1:50,000. It could be used as a *guide* for site specific studies but should not be considered as a substitute for site investigations.

3.4.2 Limitations

- The model does not reflect the full complexity of the geology. In reality, geological surfaces will be cut with igneous intrusions/vents and cut by more faults than are modelled.
- The GOCAD™ algorithm creates a triangular mesh to try and best fit all data points. For the Clyde Gateway model a mesh size of between 100–200 m was optimal. This mesh size cannot be made much smaller because there are large areas without any data points. A smaller mesh size was tested but the resultant surfaces did not appear geologically

realistic. In areas where there are abundant closely-spaced data (e.g. site investigations, or at a complex part of the outcrop line) a 100–200 m mesh size cannot represent the detail of the data density and complexity.

- Faults smaller than 30 m have not been included in the model because the data were insufficient to constrain them. There will be some areas where adjacent data points have significantly different Z values because they are offset by a fault that is not modelled.
- In summary, the meshes are a representation of the geology, using all the data but not fitting all of it exactly. The maximum deviation between a surface and a data point is about 20 m. In the majority of cases the difference between any known data point and the modelled surface is less than 5 m.
- All data points have been checked on data entry and for consistency in the model but there will be some errors that remain – for example boreholes whose site has been incorrectly located in the database, or whose start height is wrong.
- Note that to load to ArcGIS®, the modelled TIN (triangular mesh) files have been converted to grids (rectangular mesh). A grid spacing of 50 m was used so that some detail of fault gaps is preserved. This may give a false impression of the model resolution as the original TIN mesh spacing was 100-200 m. The ArcGIS® grids do not give a clean/fitted together 3D model (e.g. at fault-surface contacts) because of the TIN to grid conversion process (Figure 19). Faults 6, 14, 15 were exported with a smaller grid size of 10 m.

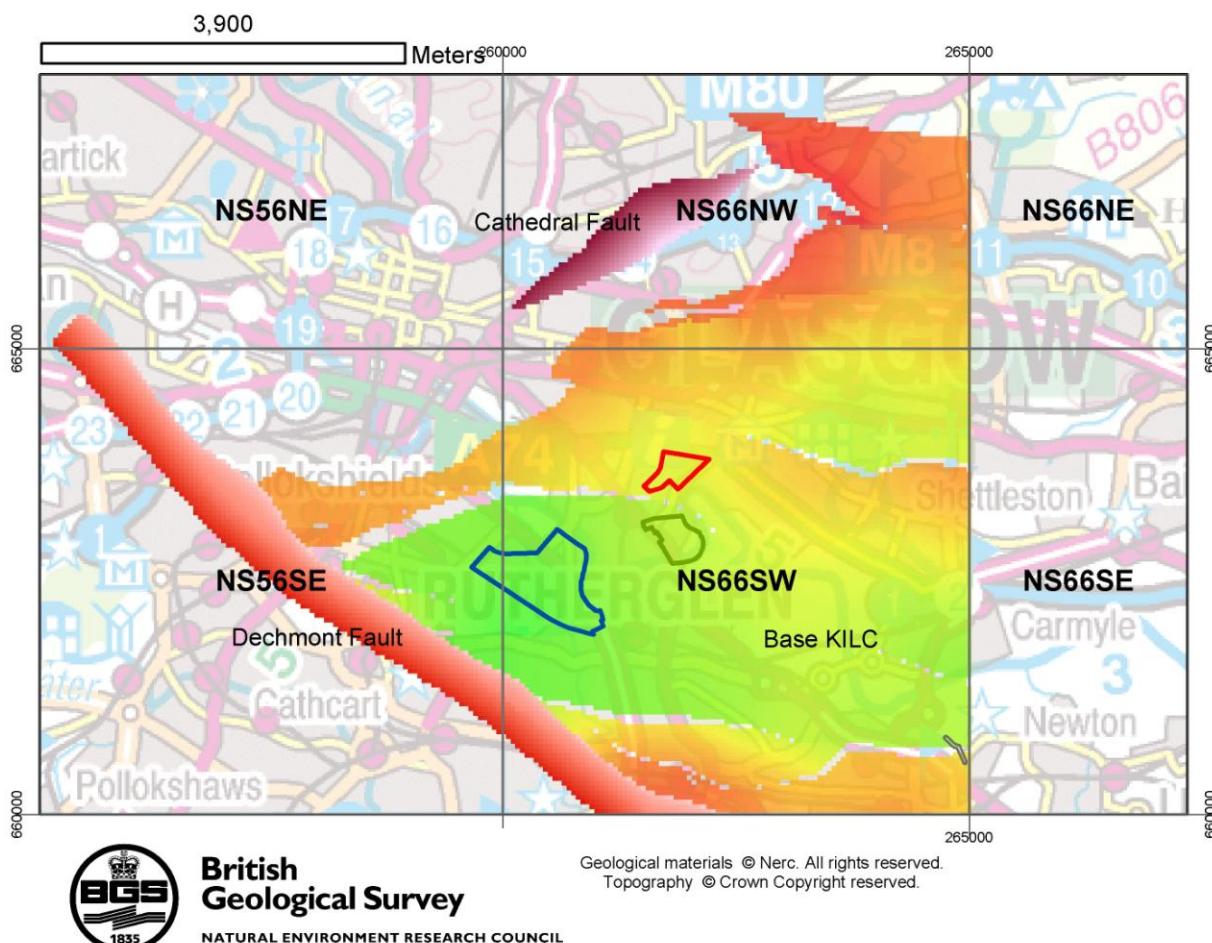


Figure 19. Example of ArcGIS® raster grid surface for KILC and two faults. Note serrated edge effect of fault gaps and outcrop due to TIN to grid conversion (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

3.4.3 Uncertainty (confidence) layers

Uncertainty layers were calculated from a combination of data density and geological complexity of the modelled surface. The data density factor includes the distribution of borehole, mine plan, and map data. Note that all the data types were given the same confidence weighting. The software is not yet sophisticated enough to vary the error of the different data types. Interpreted data was not included in the calculation. Together with the geological complexity weighting, this means a model will be most uncertain where there is little data and where the surface dip changes rapidly.

The uncertainty was calculated using the BGS confidence calculator v1.2 (see also Section 2.1.4). This is customised BGS software developed in Matlab to measure data density and geological complexity of an input Excel data file and ASCII modelled horizon grid. The output is a grid file ranked from *relative* low to *relative* high uncertainty.

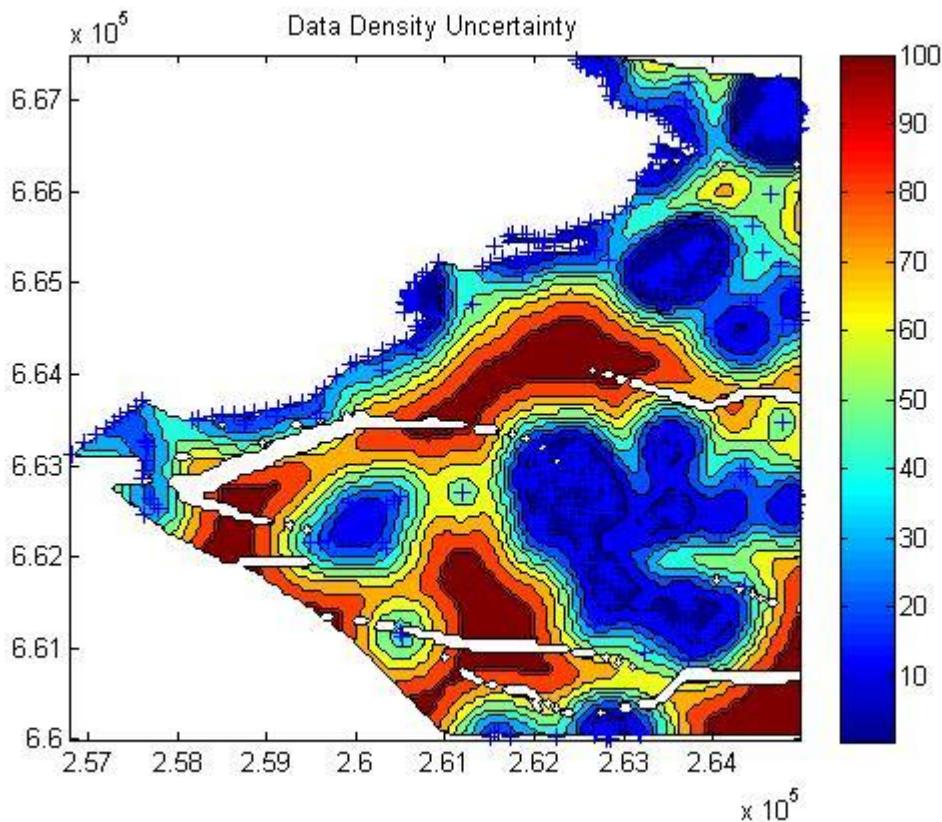


Figure 20. Example of data density uncertainty plot for KILC using an influence distance of 200 m. Data points are the blue crosses

An influence distance of 200 m and a scale of 0.5–100 were used to calculate the data density uncertainty (e.g. Figure 20).

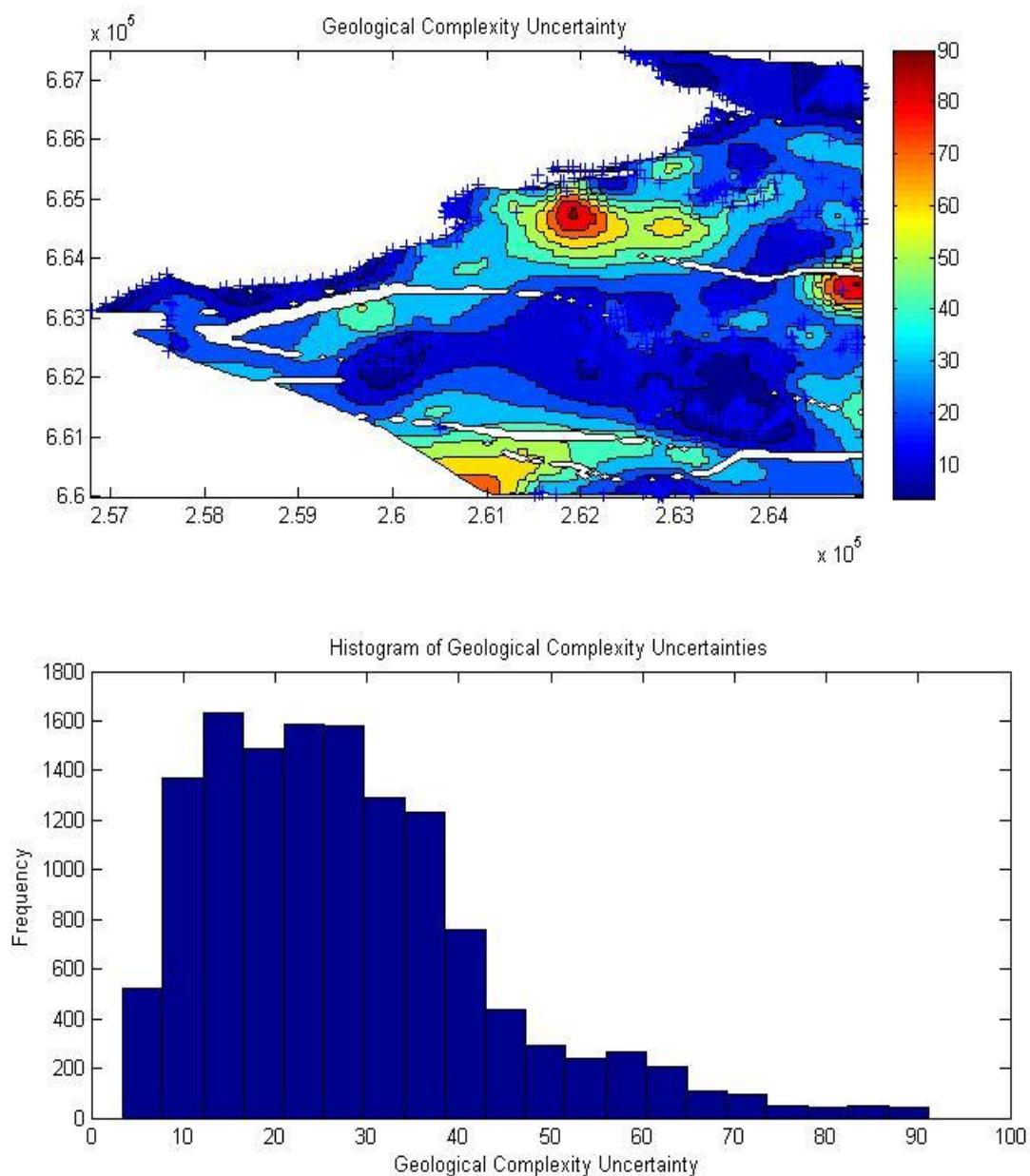


Figure 21. Example of geological complexity uncertainty for KILC model

A grid of 100 by 100 with 500 iterations was used to calculate the geological complexity uncertainty (e.g. Figure 21).

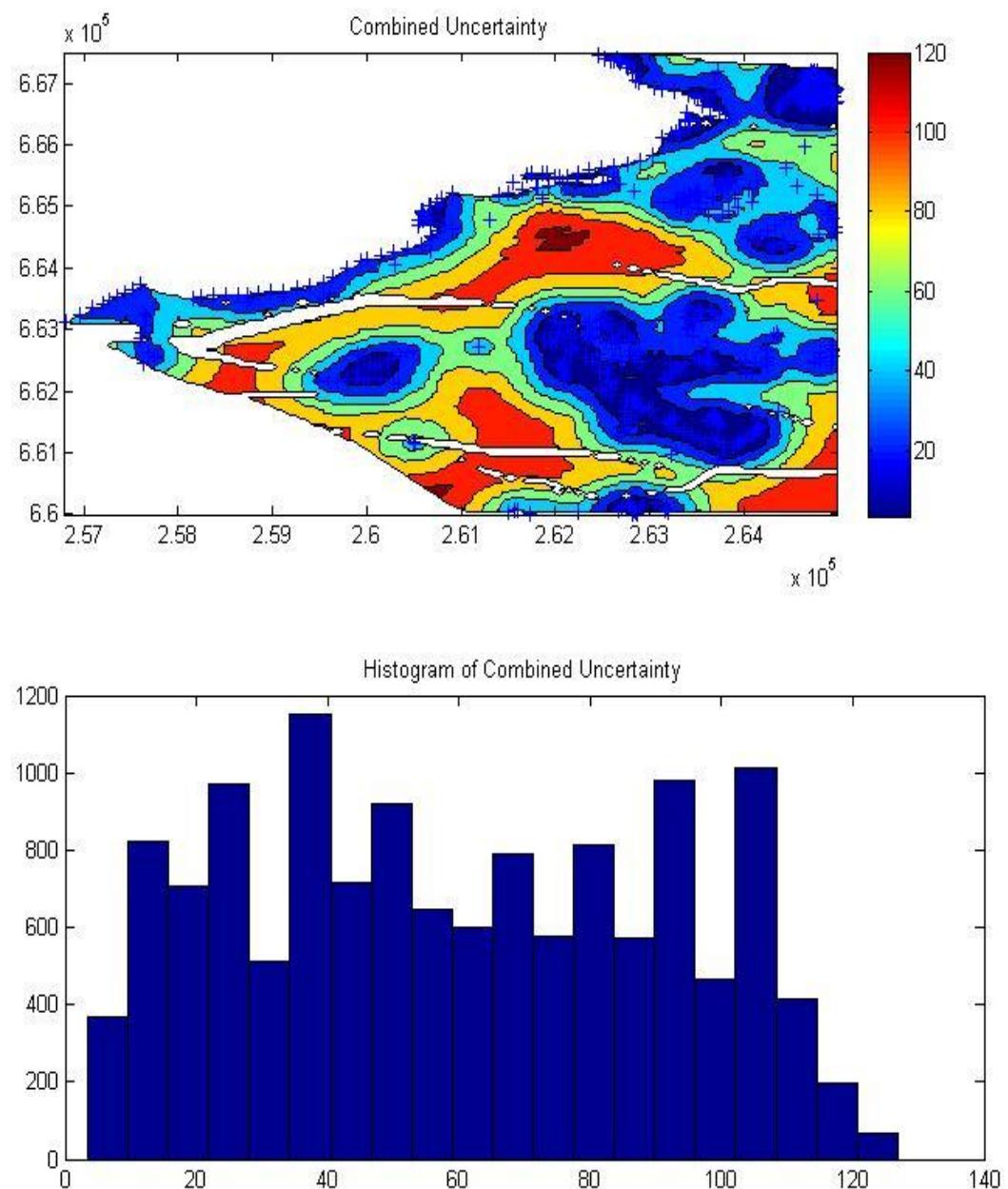


Figure 22. Example of combined uncertainty for KILC

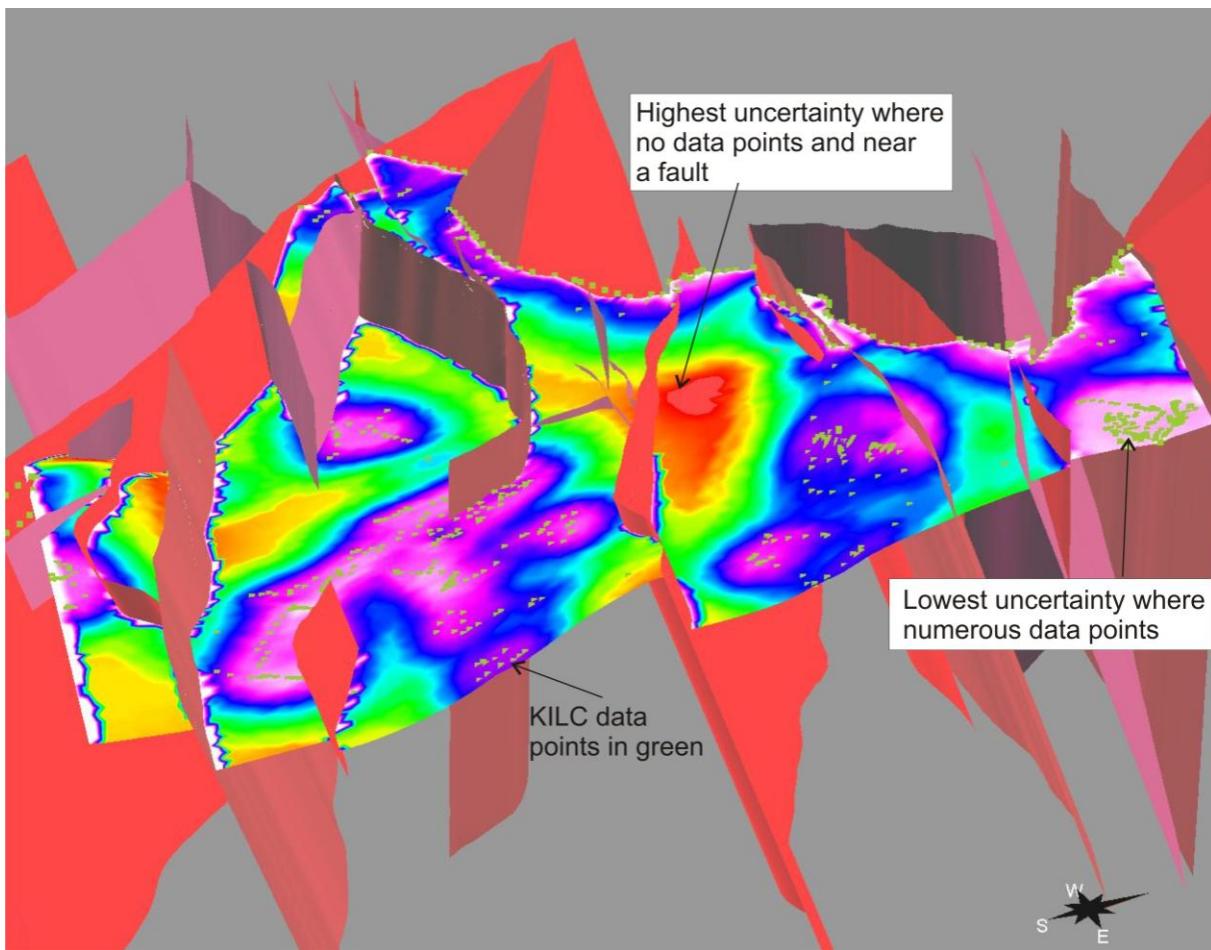


Figure 23. Example of combined uncertainty attribute for KILC draped on the geological surface in GOCAD™

The relative, combined uncertainty scale (Figures 22, 23) must be translated by the user into uncertainty categories, with the lowest number representing the lowest uncertainty and the highest number the highest uncertainty. For the Clyde Gateway model, 5 categories could be considered. In ArcGIS® this would be easy to achieve on the uncertainty raster grid by symbolising using 5 classes.

Lowest uncertainty (highest confidence) areas=1 would be those that are well constrained by geological data and where the geology is relatively simple. In these areas, the error on the model might be considered to be of the order of $\pm 10\text{m}$ in XYZ. For example, those areas of the KILC uncertainty surface on Figure 22 that are blue, or on Figure 23 that are purple or pink.

Average uncertainty (average confidence) areas = 3 would be those that are constrained by some geological data and where the geology is moderately complex i.e. faulted or folded. In these areas, the error on the model might be considered to be of the order of $\pm 30\text{m}$ in XYZ. For example those areas of the KILC uncertainty surface on Figure 22 that are green, or on Figure 23 that are turquoise-green.

Highest uncertainty (lowest confidence) areas = 5 would areas that are not constrained by any geological data and where the geology is complex i.e. faulted or folded. In these areas, the error on the model might be considered to be of the order of $\pm 70\text{m}$ in XYZ. For example those areas of the KILC uncertainty surface on Figure 22 that are red, or on Figure 23 that are orange-red.

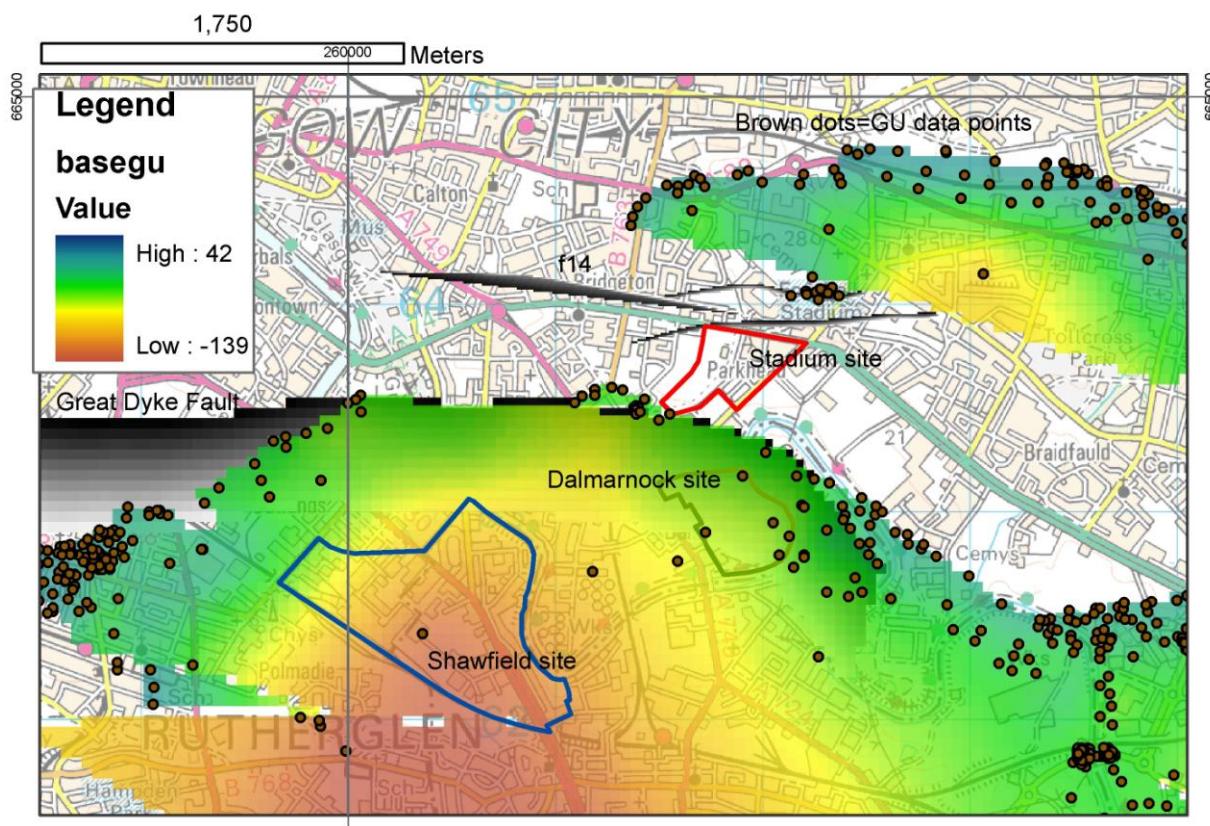
The bedrock uncertainty layers are supplied as ArcGIS® 9.2 raster grid format and in the subsurface viewer.

3.4.4 Summary of model and model limitations in key regeneration areas

This section focuses on the results and limitation of the bedrock model in the smaller, main east end Clyde regeneration area from the Shawfield site in the southeast to the NISA site to the northwest (min c. 259500,662000 max c. 262000, 664000)

The Base UCMS modelled surface is only present across the southern part of this smaller area, such as the Shawfield site, where it is present at depths from c. -20 to -60 m relative to Ordnance Datum (OD). The uncertainty on the Base UCMS modelled surface in this area is moderately low.

The Base GU modelled surface outcrops within the smaller area, between the Dalmarnock and Stadium sites and is cut by the Great Dyke Fault (Figure 24). This is of particular note because the GU coal is commonly mined out. The surface is at depths of c. -120 m to -80 m relative to OD over the Shawfield site and close to outcrop at depths of -40 to -60 m over the Dalmarnock site. The uncertainty on the Base GU surface is low-moderately low over the Dalmarnock site and higher over the Shawfield site. There are likely to be faults with throws less than 30 m in this area that cut the GU but which have not been modelled.



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Figure 24. ArcGIS® grid of the Base GU surface and constraining data points. (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

The Base GE modelled surface has a complex outcrop pattern within the smaller area, including cutting across the Stadium site. It is cut by the Great Dyke Fault, f6, f14 and f15 (Figure 25). This position close to outcrop is of particular note because the GE coal is commonly mined out. The surface is at depths of c. -150 m to -100 m relative to OD over the Shawfield site, depths of

-65 to -80 m over the Dalmarnock site, and -50 to -24 m at outcrop over the Stadium site. The uncertainty on the Base GE surface is low-moderate over the Stadium and Dalmarnock sites and moderately high over the Shawfield site. There are likely to be faults with throws less than 30 m in this area that cut the GE but which have not been modelled.

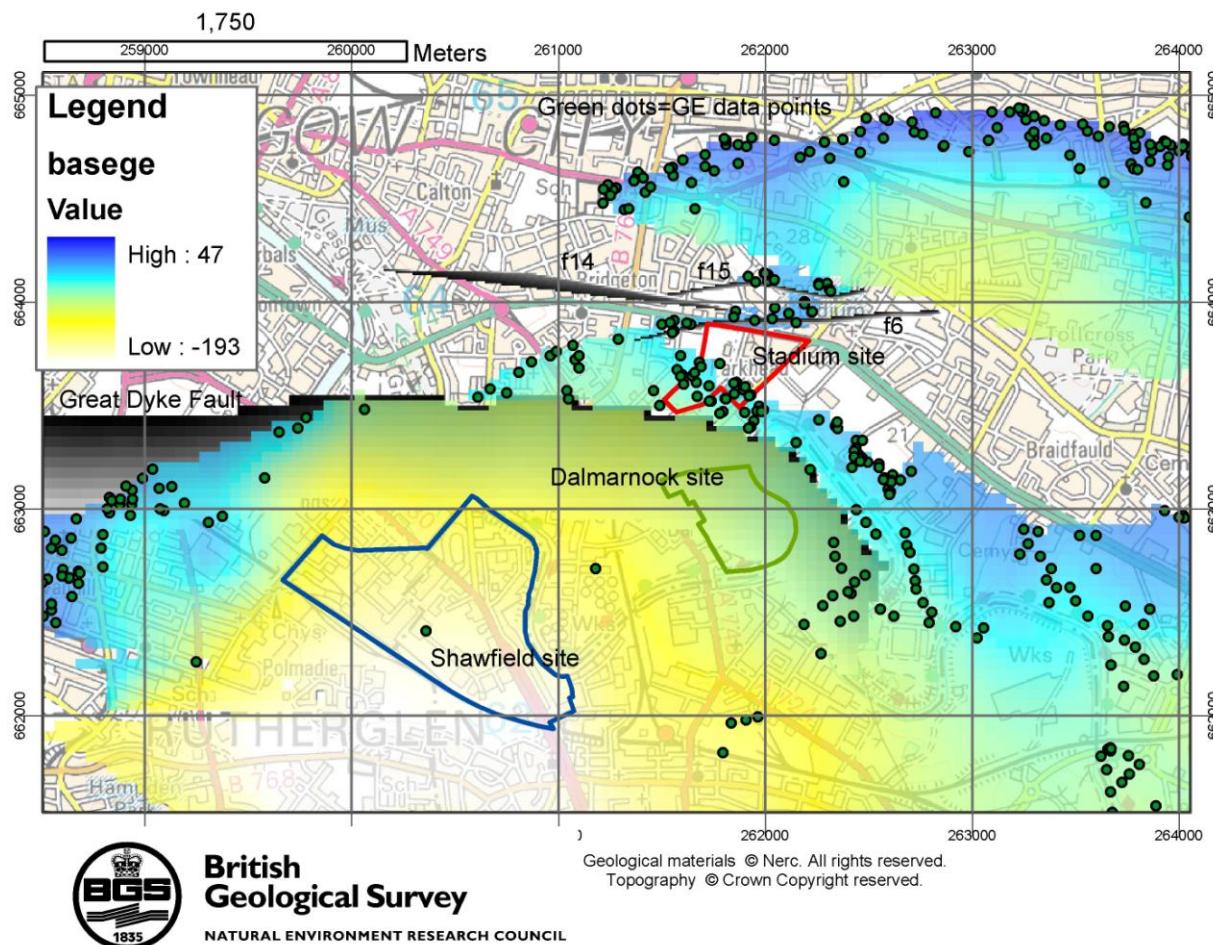


Figure 25. ArcGIS® grid of the Base GE surface and constraining data points (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

The Base KILC modelled surface is present at depth across all of the smaller area. It is cut by the Great Dyke Fault. The surface is at depths of c. -260 m to -110 m relative to OD. The uncertainty on the Base KILC surface varies from low-moderate across the area (Figure 22).

The Base ULGS modelled surface is present at depth across all of the smaller area. It is cut by the Great Dyke Fault. The surface is at depths of c. -300 m to -250 m relative to OD. The uncertainty on the Base ULGS surface varies from moderate to high across the area as there is no constraining data.

The Base KDG modelled surface is present at depth across all of the smaller area. It is cut by the Great Dyke Fault. The surface is at depths of c. -500 m to -330 m relative to OD. The uncertainty on the Base KDG surface varies from moderately high to high across the area as there is no constraining data.

4 Groundwater model

4.1 CONCEPTUAL MODEL

4.1.1 General hydrogeology of the groundwater system

The superficial deposits sequence in the Clyde Gateway area, and across the whole of Glasgow – represented in the GSI3D model by 15 stratigraphic layers – is likely to form a complex multilayered aquifer or series of aquifers, in which coarser-grained horizons (gravels and sands) act largely or wholly as separate aquifers, separated by lower permeability finer-grained deposits (clays and silts). Groundwater flow paths are likely to be restricted by this partitioning and therefore to be relatively local.

The aquifer properties (hydraulic characteristics) of the various geological units are largely unknown. No pumping test data were available for the Glasgow area to provide measured values of transmissivity, hydraulic conductivity/permeability¹ or storage capacity of the aquifer units. These properties have therefore been estimated based on available data for similar hydrogeological units in other areas.

4.1.2 Context and extent of groundwater modelling

Groundwater modelling has been undertaken to simulate groundwater flows within the superficial deposits of the Clyde Gateway area of Glasgow. The basis for the groundwater model has been the geological structure provided by the GSI3D model. However, the groundwater model covers a different extent than the GSI3D model, for the reasons given below, and so additional geological information has been used to develop the groundwater model outside the area of the GSI3D model.

The main area of interest is the area covered by the GSI3D model (1:10,000 map sheets NS66SW, NS66NW and NS56SE). However, the groundwater system boundaries are much larger than this area. Effective modelling of the groundwater system requires the assessment of a whole groundwater catchment, the boundaries of which can be defined with reasonable certainty. Groundwater model boundaries are best defined at physical features such as contacts between aquifers and less permeable geological units, or lakes or water bodies. These are zones where groundwater head (level) or flow can be measured or estimated with reasonable certainty, such as a no-flow boundary (e.g. a contact between an aquifer and an effectively impermeable rock), or a fixed (constant) groundwater head boundary (e.g. a contact between an aquifer and a large lake).

The maximum extent of the groundwater model therefore encompasses a significantly larger area than the GSI3D model. However, it has been developed with increasing levels of refinement and complexity as the model ‘zooms’ in to the main area of interest in the area covered by the GSI3D model:

- The largest modelled area is for the recharge model, which covers a maximum extent of the whole Clyde catchment. Within the recharge model, there are two levels of refinement: the coarsest across the whole catchment, and the more refined across the Glasgow urban area.
- The maximum extent of the groundwater flow model has been defined as the approximate limit of significant thickness of superficial deposits in the Clyde valley in the Glasgow area: that is, the areas where the outcrop pattern of superficial deposits in

¹ In this report, the terms *hydraulic conductivity* and *permeability* are used interchangeably.

the Clyde valley begins to become patchier on the higher ground to the north and south of the River Clyde, and bedrock begins to be exposed at the ground surface (Figure 26). This assumes that the superficial deposits in these areas are thin and that therefore there are negligible groundwater flows within the superficial deposits across this boundary. The boundary is therefore assumed to be impermeable for the purposes of the model. This modelled area covers the whole of the Glasgow urban area, stretching approximately 27 km from Johnstone in the west to Coatbridge in the east and approximately 15 km from Barrhead in the south to Milngavie in the north (Figure 27). The available geological information and the process of constraining the modelled aquifers in this area are described below.

- The groundwater flow model is refined for the area of the GSI3D model. However, the extent and shape of the GSI3D model area is not ideal for the purposes of modelling groundwater flow. The ZOOM grid is rectangular and therefore requires a similar shaped area for simulating the groundwater system. The refined area of the groundwater flow model has therefore been extended into 1:10,000 map sheet NS56NE. The available geological information and the process of constraining the modelled aquifers in this square, outside the GSI3D model, are described below.

4.1.3 Setting up the hydrogeological structure

Within the area of the GSI3D model, the GSI3D geological layers have been used as the basis for defining the hydrogeological layers in the groundwater model. This is not a simple process of matching layer-for-layer, but an interpretation and simplification process. Many of the distinct geological layers are assumed, based on the available data, to have essentially the same hydrogeological properties – for example, all sand and gravel units are assumed to have generally high permeability with relatively high storage capacity, whereas clay units are assumed to have generally low or negligible permeability and storage capacity. For the purposes of modelling, the various geological units represented in the GSI3D model have been combined into three hydrogeological units in only two layers. These represent three broad categories of aquifer permeability. These are a *high permeability* layer near the ground surface; and an underlying layer that has been subdivided into a zone of *moderate permeability*, representing units dominated largely by fine sands; and a zone of *low permeability*, representing units dominated by silts and clays. The three hydrogeological units are illustrated in the cross sections in Figure 29. In the absence of quantitative data on local aquifer hydraulic properties, the numerical values for the permeability of each zone/layer are based on available data for similar hydrogeological units in other areas. A summary of the permeability values used in the model is given in Table 3. These were varied in the model runs, and the model results compared with available valuation data, in order to refine the estimated values. The preferred final permeability values based on the results of the modelling are presented in Section 4.4.3.

The underlying Carboniferous bedrock forms a third layer in the model, undivided, for the purposes of specific model runs (see Section 4.3).

To expand the refined groundwater flow model into square NS56NE, additional detailed geological information from borehole logs was interpreted.

To expand the refined groundwater flow model, covering the four 1:10,000 map squares, across the full groundwater flow model area, a simple interpolation method was used. This assumed that at the outer groundwater flow model boundary, the superficial deposits have a small constant thickness of 2 m. Between this boundary and the edge of the refined groundwater flow model, the hydrogeological layer thickness was calculated by linear interpolation from selected points at the boundaries of the GSI3D model (Figure 28).

4.1.4 Available groundwater data, flow and recharge

Available groundwater level (or groundwater head) data are sparse for Glasgow. A detailed description of the currently available data, and of the issues involved in interpreting groundwater level data, is given in Ó Dochartaigh (2009). In summary, the available information shows that groundwater levels in superficial deposits in Glasgow are usually between 3 and 10 m below ground level (mbgl), but can range from less than 1 to nearly 50 mbgl. Taking ground elevation into account, measured borehole groundwater levels range from approximately 1.0 to 75.0 m above Ordnance Datum (AOD). Groundwater levels appear to be variable both spatially and over time. In some cases, adjacent boreholes show significantly different groundwater levels; for example, boreholes less than 50 m apart have recorded groundwater levels that vary by more than 10 m. This highlights the complexity of the heterogeneous superficial deposits aquifer with different hydrogeological units showing different hydraulic (groundwater) heads. Groundwater levels have also been observed to vary in response to tidal changes (close to the River Clyde) and to seasonal changes; the time-series groundwater level datasets that have been collected are not yet long enough to infer any longer-term variations.

Groundwater flows within the superficial deposits are generated by direct (rainfall originated) and indirect recharge (leakages from rivers, mains water and sewer pipes). The widespread presence of impermeable surface sealing across the urban area will restrict rainfall recharge, but it is still likely to be an important input through the large area of gardens and parks. The volume of recharge from leakage from rivers and urban flows will depend partly on the volume of those flows, partly on the characteristics of the river beds, water pipes and the surrounding manmade and natural geological surrounding materials – which will control leakage rates – and partly on local groundwater conditions (whether the river or pipe is above or below the local groundwater level).

Most of the groundwater flow is likely to be largely lateral: towards, and discharging to, the River Clyde and its tributaries. Some recharge to the underlying bedrock aquifer is likely to occur where hydrogeological conditions allow vertical flow. Groundwater may also be collected by sewers and culverts, from where it also discharges to the Clyde tributaries or the River Clyde itself. No abstraction from superficial deposits aquifers is known to occur within the groundwater model area. Groundwater heads and flows are controlled, therefore, only by the locations and bed elevations of the River Clyde and its tributaries and by the spatial variations in the hydraulic characteristics of the modelled hydrogeological layers and their thicknesses.

4.1.5 Uncertainties

- The quality of the geological modelling highly depends on the availability of the boreholes and geological logs. The quality of the geological model and the associated uncertainty is described elsewhere in this report.
- Aquifer layer thicknesses outside the area of the GSI3D model are highly uncertain. They are calculated based on a linear interpolation and on the assumption that the layers are 2 m thick at the edges of the groundwater flow model. This is expected to affect the model results and must be accounted for when interpreting them.
- Because the aquifer hydraulic characteristics of the geological units are largely unknown, there is uncertainty in the assigned values for transmissivity, hydraulic conductivity and storativity of the aquifer units.
- The ratio of the horizontal hydraulic conductivity to the vertical hydraulic conductivity is unknown. This makes the modelled vertical movement of groundwater flows between the aquifer layers less certain.

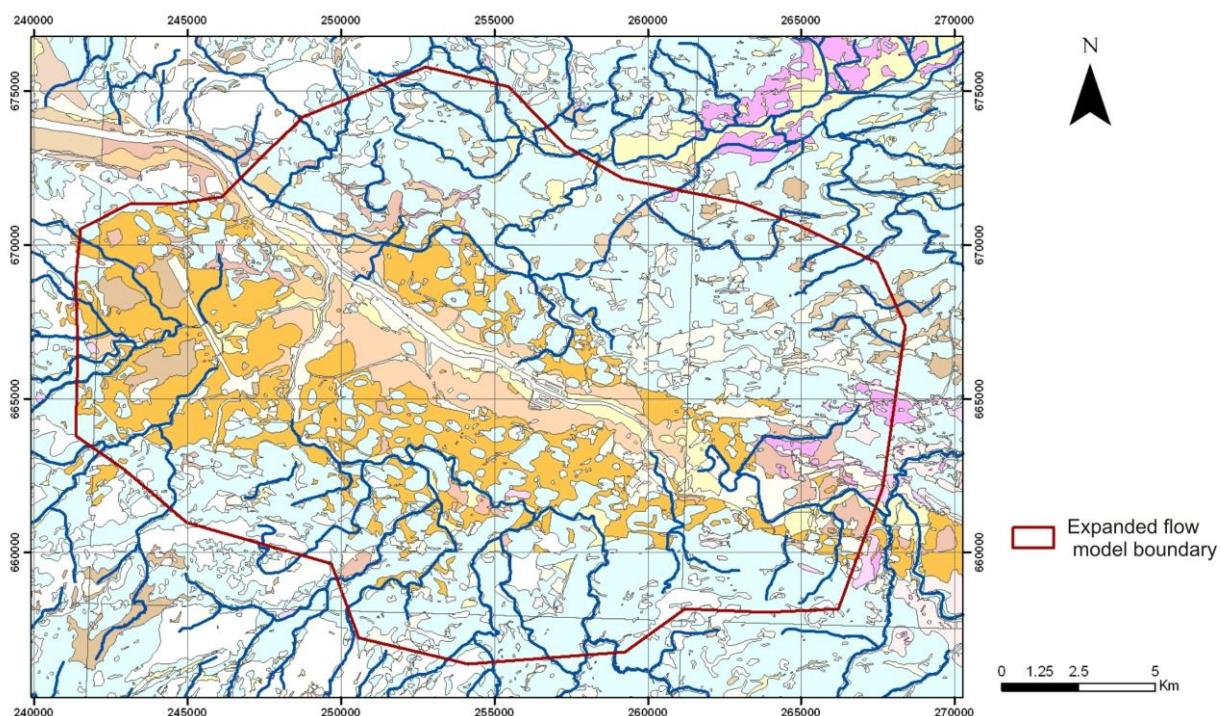


Figure 26. Groundwater flow model area, with 1:50 000 scale superficial geology DiGMap layer and tributaries of the River Clyde (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

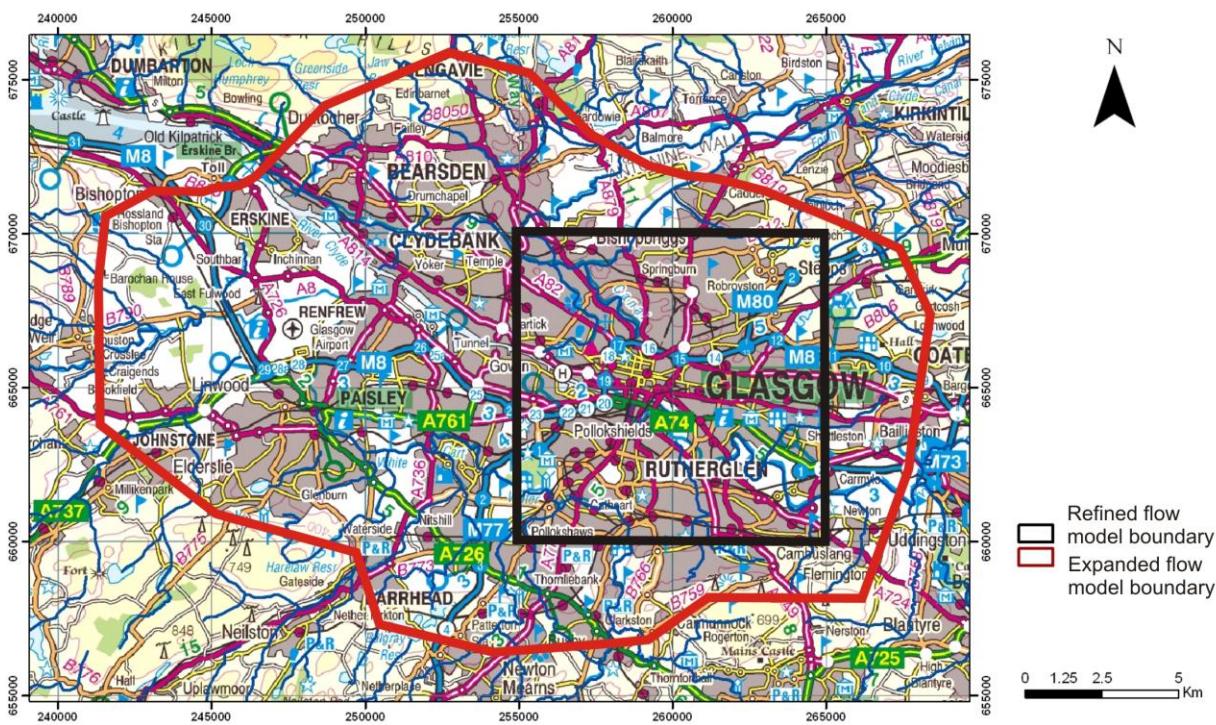


Figure 27. Groundwater flow model area: maximum extent and refined area. (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

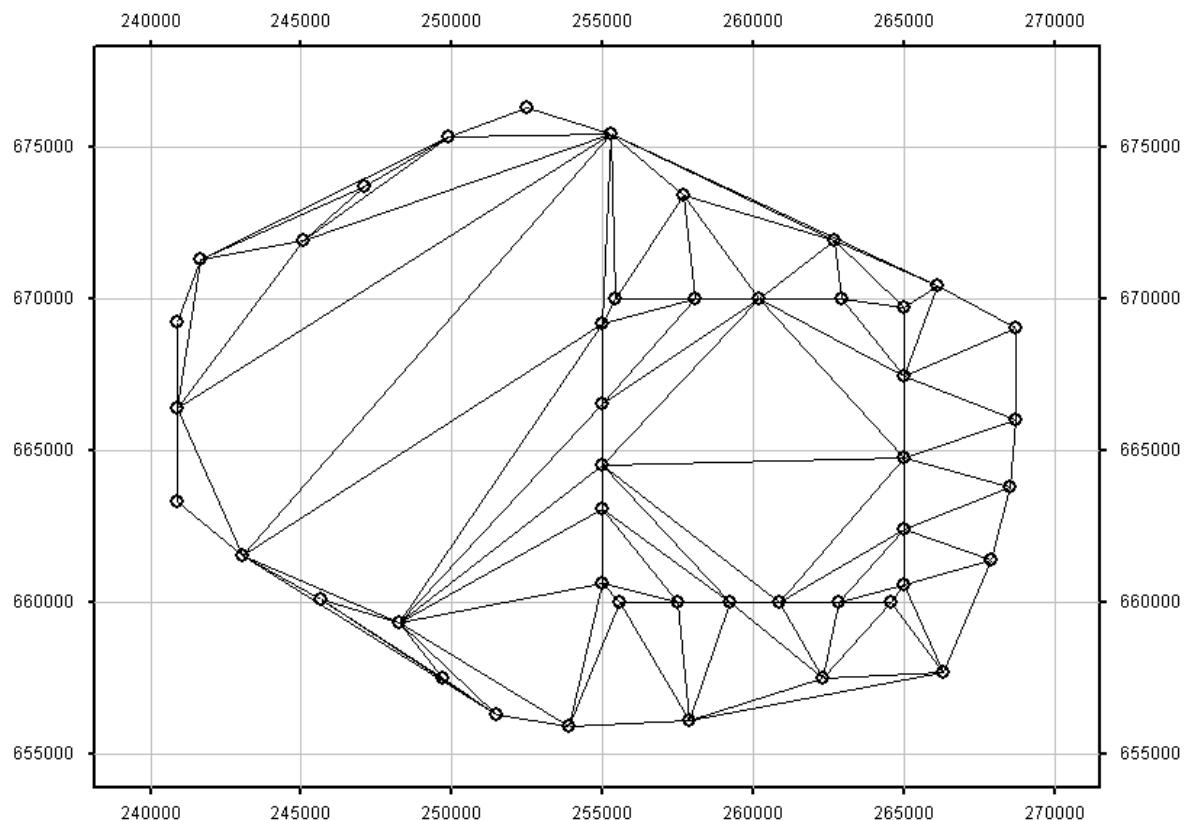


Figure 28. Triangular planes for the interpolation of superficial deposits thicknesses outside the refined groundwater flow model area

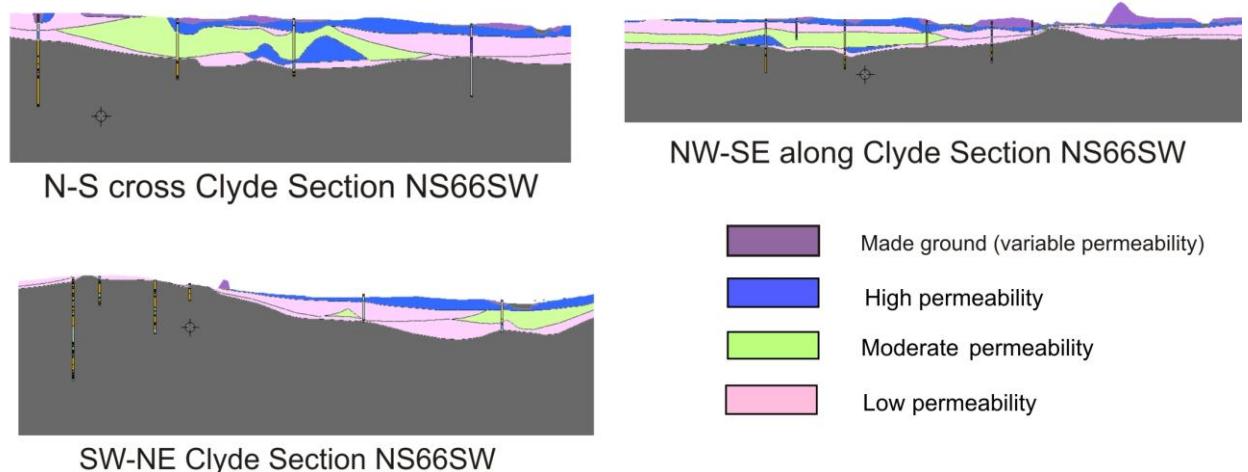


Figure 29. Geological cross-sections interpolated by a qualitative classification of aquifer permeability

4.2 RECHARGE ESTIMATION

4.2.1 Introduction

Long-term average recharge values over the area of the groundwater flow model have been estimated using the distributed recharge model ZOODRM (Mansour and Hughes, 2004). The model applies the soil moisture deficit (SMD) method, which is based on the work of Penman (1948) and Grindley (1967), to calculate actual evaporation, changes in soil moisture, and recharge. The model uses daily rainfall and monthly potential evaporation in combination with landuse type, topography and run-off coefficients from data files and calculates surface run-off and recharge values. However, large parts of the area of interest are highly urbanised. This leads to enhanced surface run-off as well as to the generation of indirect recharge from leakage from pressurised water mains and damaged storm and sewage sewers. There is also significant water transfer from impermeable features such as roofs to open areas like gardens. Under these circumstances, conventional recharge calculation methods – for example the SMD method – are not applicable, and alternative methods must be developed. ZOODRM has been refined to include a calculation method that better represents the key recharge mechanisms in urban areas. The average recharge values calculated over the simulation period are used in the groundwater flow model to simulate the groundwater flow movement in the superficial deposits aquifers.

4.2.2 Description of the recharge model ‘ZOODRM’

ZOODRM is a distributed recharge model that allows the estimation of recharge based on three calculation methods. These are the conventional Soil Moisture Deficit (SMD) method (Penman, 1948 and Grindley, 1967), the Environment Agency / FAO method (Hulme et al., 2002), and a specific method for recharge calculation in semi-arid areas (Hughes et al., 2008). A daily time step is used for the recharge calculation. Each grid node is linked to a rain gauge by means of Theissen polygons to obtain the daily rainfall and potential evaporation (PE) values. These values are varied across the model nodes and located within one polygon by multiplying them by the ratio of the long term average (LTA) rainfall and LTA PE values calculated at the weather station and LTA rainfall and PE values at the grid nodes. LTA rainfall and potential evaporation (PE) values are estimated at the grid nodes by contouring the LTA rainfall and PE values at the weather stations and producing a gridded map of these contour lines.

The model can also simulate indirect recharge processes originating from routing surface water run-off water to rivers and ponds (the term *pond* is used to refer to any temporary or permanent surface water store), leakage through riverbeds, and routing water in the soil zone. A run-off coefficient is used to calculate run-off as a percentage of total rainfall at each node. A Digital Terrain Model (DTM) provides slope aspect and routes the calculated run-off from each grid node to the relevant surface water feature. Water in the soil zone can be routed horizontally to rivers or to other discharge points such as springs. A soil zone groundwater velocity factor, which can be varied spatially, is used for this purpose. The presence of the unsaturated zone can be taken into account in the model by including a lag between the time the estimated recharge leaves the soil zone and the time it reaches the water table. This lag time can be also varied spatially. Figure 30 illustrates the different classes of the numerical objects, prefixed with letter C, and the methods of calculations included in the ZOODRM model.

ZOODRM allows local grid refinement to increase the resolution of the recharge calculations over discrete areas. This makes the recharge model fully compatible with the groundwater flow model ZOOMQ3D (Jackson and Spink, 2004): i.e., a separate recharge value is calculated by the recharge model at all the grid nodes in the flow model. The grids of recharge values (e.g. Figure 34) are automatically read by the flow model.

4.2.3 ZOODRM recharge mechanisms in urban areas

Key recharge mechanisms identified in urban areas include enhanced overland flows from buildings, car parks and roads, which increase the indirect recharge, and the direct recharge from back gardens, open spaces and parks which lose water directly from their soil zone to the saturated zone. The recharge calculation, however, is complicated by the transfer of water from one landuse type to another within the same model grid node: for example, the water movement from house roofs to back gardens.

The new ZOODRM recharge calculation can deal with the following four landuse types:

- pavements and roads (landuse type 1),
- buildings (landuse type 2),
- gardens (landuse type 3), and
- parks and open green spaces (landuse type 4).

ZOODRM deals with surface water and recharge generated at the different landuse types at each node by calculating the surface run-off and recharge for each landuse type, and proportioning the results using the corresponding percentage landuse values at that node. A more detailed description of the method can be found in Mansour et al. (2008).

The numerical calculations of recharge and generated run-off at each node are then undertaken as follows:

Pavements and roads (landuse type 1) receive water from rainfall and adjacent buildings. These surfaces are not completely impermeable, and a proportion of water is known to infiltrate and become recharge, for example through pavement cracks. The model allows 20 % of water received by pavements and roads to become recharge, while the remaining water is transferred to run-off. A run-off coefficient is defined to determine the volume of water transferred to surface water courses and the volume of water infiltrated into the ground.

Buildings (landuse type 2) transfer the rainfall they receive to pavements and roads and to gardens (landuse type 3) according to the following criteria:

Typically a house is bound by a road at the front and a garden at the rear. Consequently, part of the rainfall will be transferred to the road and the other part will be transferred to the garden. If the area occupied by houses in a numerical urban node is equal to or greater than the area occupied by gardens half of this rainfall is transferred to gardens. Otherwise the following formula is used to determine the fraction of rainfall transferred to the garden:

$$\text{House_Garden} = 0.5 \times (\text{Percentage gardens (landuse type 3)}) / \text{Percentage buildings (landuse type 2)}.$$

The remaining fraction will be transferred to roads.

If the percentage of houses is greater than zero but the percentage of pavements and roads is zero, it is assumed that all the water transferred from houses to roads is overland run-off water, i.e. not reaching the storm sewers. This overland water is routed to the nearest river node based on the topographical gradient.

The conventional soil moisture deficit (SMD) method is applied to calculate the recharge over gardens. Any rainfall received from buildings is added to the rainfall before calculating the run-off and recharge values.

An urban node may also include open green spaces and other specified landuse types. These landuse types can be added to the urban nodes on the condition that the SMD method applies to recharge calculations over them.

4.2.4 Construction of the recharge model

In order to improve the estimation of recharge values and construct an accurate water balance, it is important to include the direct and indirect recharge mechanisms occurring outside the area of the groundwater flow model. This ensures more reliable estimates of recharge at the flow model boundaries, as well as of groundwater inflows into the flow model across the model boundaries.

The boundary of the recharge model is typically taken as coincident with the boundary of the surface water catchment; in this case this has been taken as the whole Clyde basin (Figure 31). This area is much larger than the Glasgow city boundary; however, dealing with such a large scale is possible when using ZOODRM because of its grid refinement capability. A coarse grid is laid over the whole catchment area to account for the key recharge mechanisms occurring outside the area of interest, while refined grids are defined over the areas where high resolution recharge values are required.

The total recharge model area is approximately 3100 km², with the Glasgow conurbation occupying the northwest part of the area (Figure 31). Apart from this highly urbanised part, where the refined urban recharge calculation method is applied, the landuse is dominantly moorland, grassland, and arable farming. Forestry and broadleaved woodlands are also present in the centre of the basin. The conventional SMD recharge calculation method is applied over these areas.

A coarse model grid with 1000 m square cells is used to cover the whole Clyde basin area. A refined grid with 100 m square cells covers the Glasgow area (Figure 31). A gridded map file is used to specify the areas over which the SMD or the urban area recharge calculation methods are applied. Values for the different plant root constants and wilting points for the SMD recharge calculation method are obtained from Lerner et al. (1990).

The Centre for Ecology and Hydrology Digital Terrain Model (DTM) (Morris and Flavin, 1990) has been used to derive the topographical gradient values and the aspect directions used in the surface flow routing. Major rivers and streams are included using a rivers model object within ZOODRM. It is possible to include the storm water sewers within Glasgow in the model by using these rivers objects. Indirect recharge caused by water leaking from these sewers can then be accounted for using a river leakage coefficient. The value of this leakage coefficient determines the percentage of total water which reaches each river node that is lost to the underlying aquifer. The sewer network within the Glasgow area is complex, and it is not possible to include it all in the recharge model. As a working assumption, only culverts and sewer pipes with heights or diameters greater than 800 mm have been added to the modelled river network. Surface water generated over the catchment area is routed to the open (real) rivers and to the modelled rivers that represent sewers and culverts, with routing based on surface flow paths specified using the aspect directions map from the DTM.

Sixty six rainfall gauging stations, each holding daily rainfall data for the period from 1961 to 1997, have been used to distribute rainfall over the catchment area for the recharge model. Grid nodes have been related to the gauging stations based on Theissen polygons, which are constructed based on the distribution of the gauging stations (Figure 32). The long-term average (LTA) rainfall values at the gauging stations have also been contoured to provide a map of distributed LTA rainfall values. The values of this map, together with the LTA values at the gauging stations, have been used to calculate the daily rainfall value at each of the grid nodes. The daily rainfall at a node is calculated by multiplying the daily rainfall value at its related gauging station by the ratio of LTA rainfall value (obtained from the map of distributed LTA rainfall values at the node location) to the LTA rainfall at the related gauging station. This approach produces gradual changes in the rainfall values from one Theissen polygon to another. The available period of rainfall record (1961 to 1997) is adequate to produce reliable long term average recharge values in order to undertake steady state simulations of groundwater flows. Rainfall data at individual gauging stations may cover shorter periods than the full time series. In

this case, the model uses a pre-defined substitute gauging station to obtain a rainfall value for a specified date.

Potential evaporation data have been obtained from the Meteorological Office's MORECS data set for Squares 48, 49, 50, 55, 56, 57, 62, 63 and 64 (Figure 33). Potential evaporation time series for these squares are available on a monthly basis covering the period from 1961 to 2006. These have been converted to daily values by dividing by the number of days in each month.

Leakage from pressurised water mains has been incorporated in the recharge model by assuming a constant leakage rate that is evenly distributed over the model nodes located within the urban areas. A total consumption rate of approximately 600 Ml day^{-1} from pressurised water mains is used in the model, based on available data supplied by Scottish Water. A leakage rate of 10% has been assumed as a first approximation. It is recognised that leakage rates in specific areas are often higher than this, but reliable information is difficult to obtain, and a 10% leakage rate was set as a useful working average across the whole urban area. With a total urban area of approximately 260 km^2 , this yielded an additional recharge load of 0.23 mm day^{-1} over each of the urban nodes.

A map of the calculated distributed recharge values is shown in Figure 34.

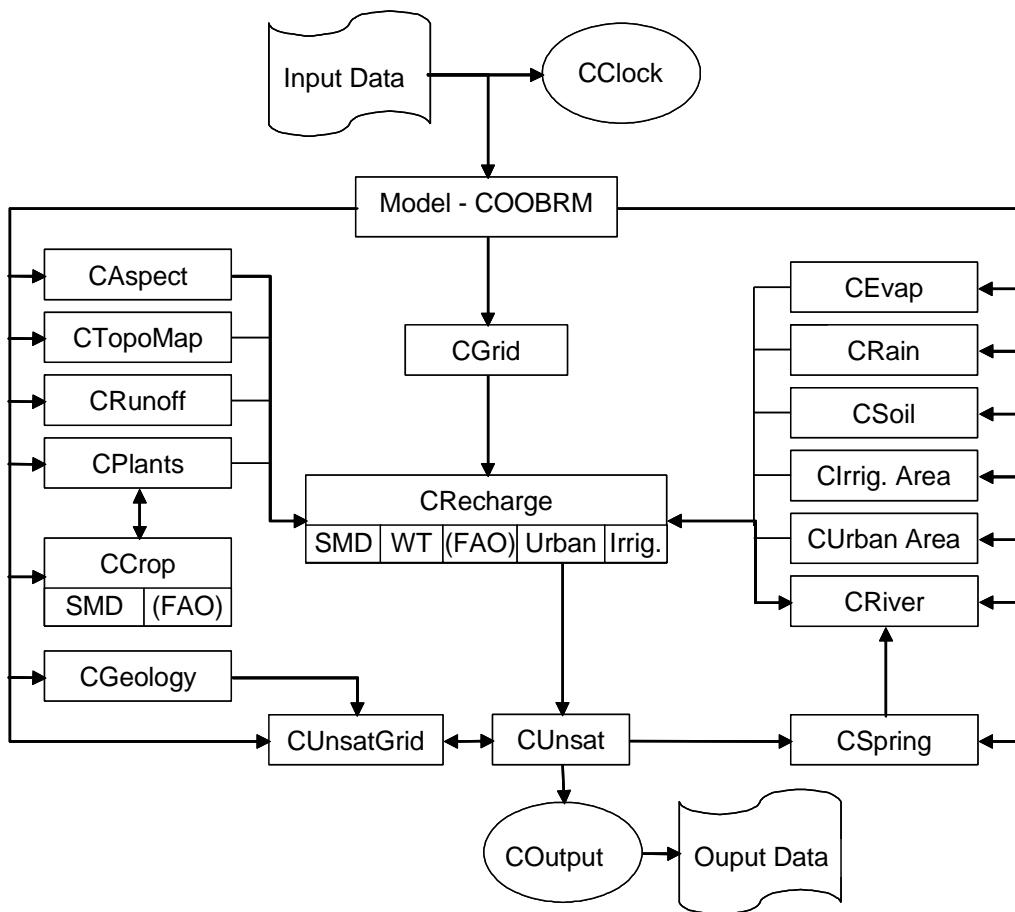


Figure 30. Framework of the recharge model

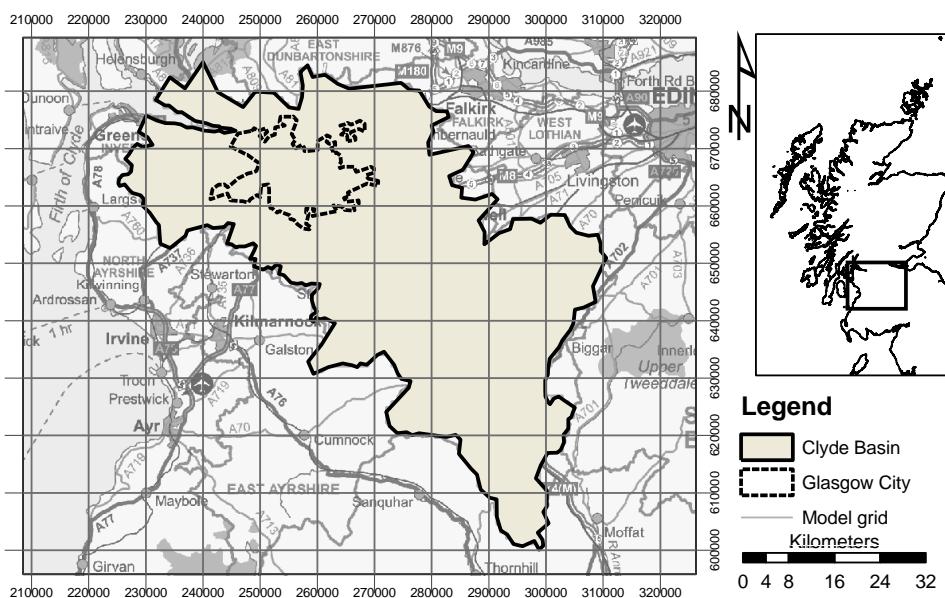


Figure 31. Extent of the recharge model across the Clyde basin area, showing refined areas across Glasgow and the Clyde Gateway area. (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

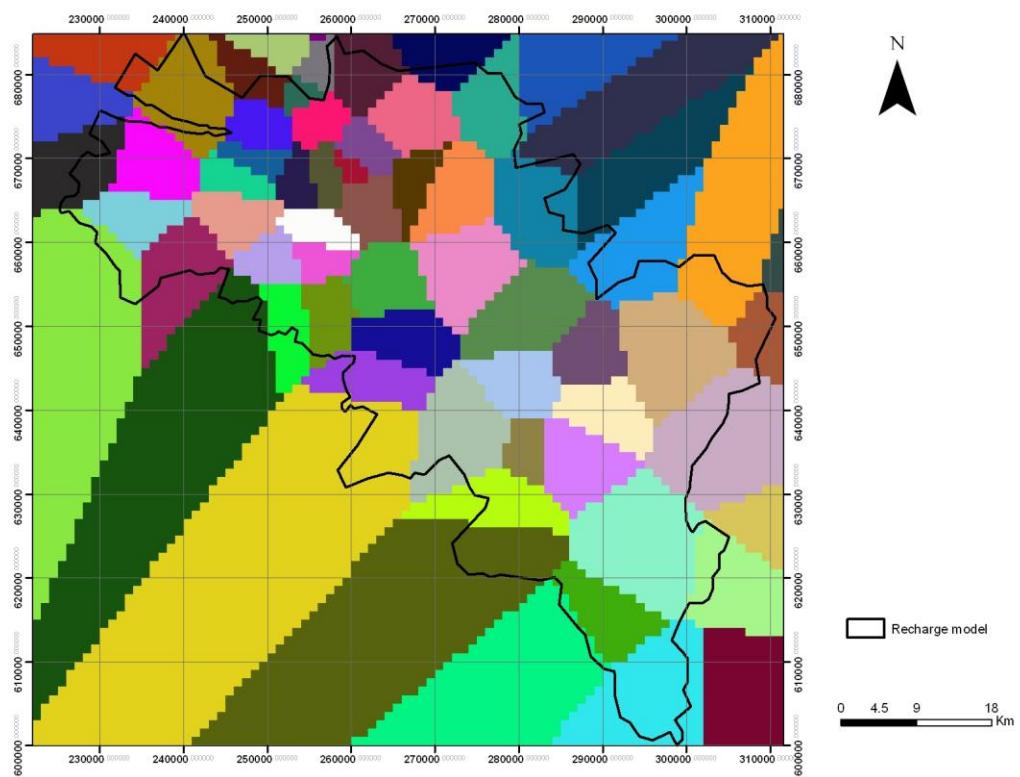


Figure 32. Rainfall Theissen polygons

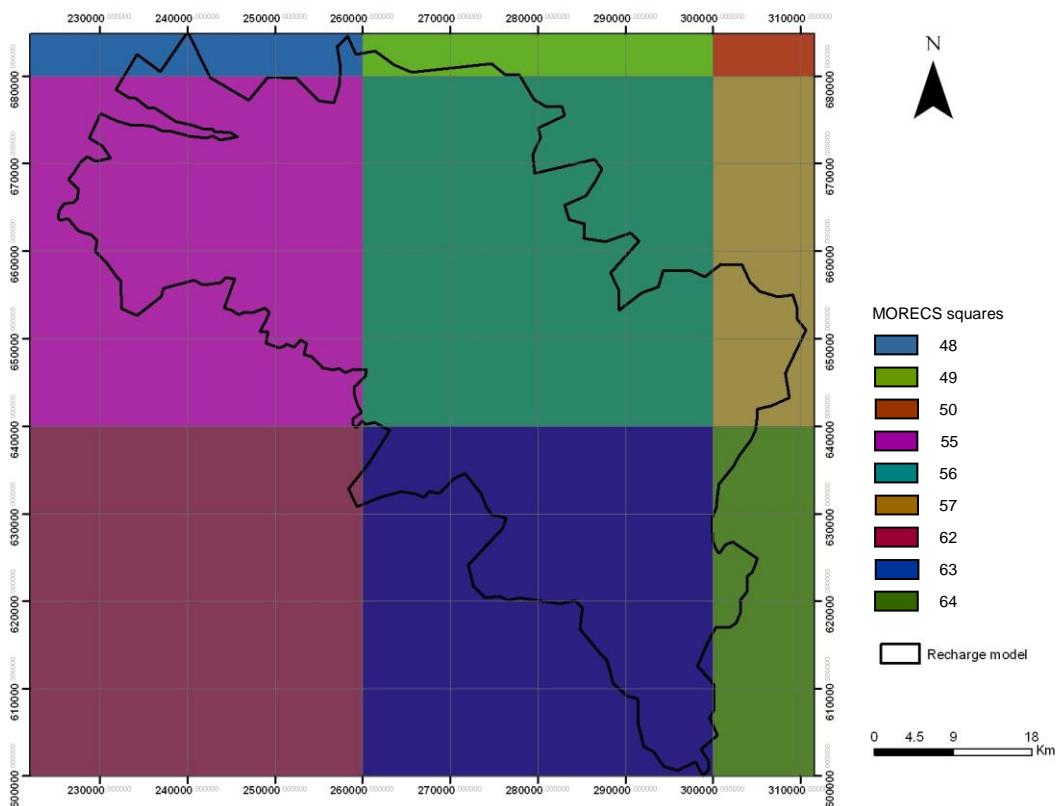


Figure 33. MORECS squares for potential evaporation data

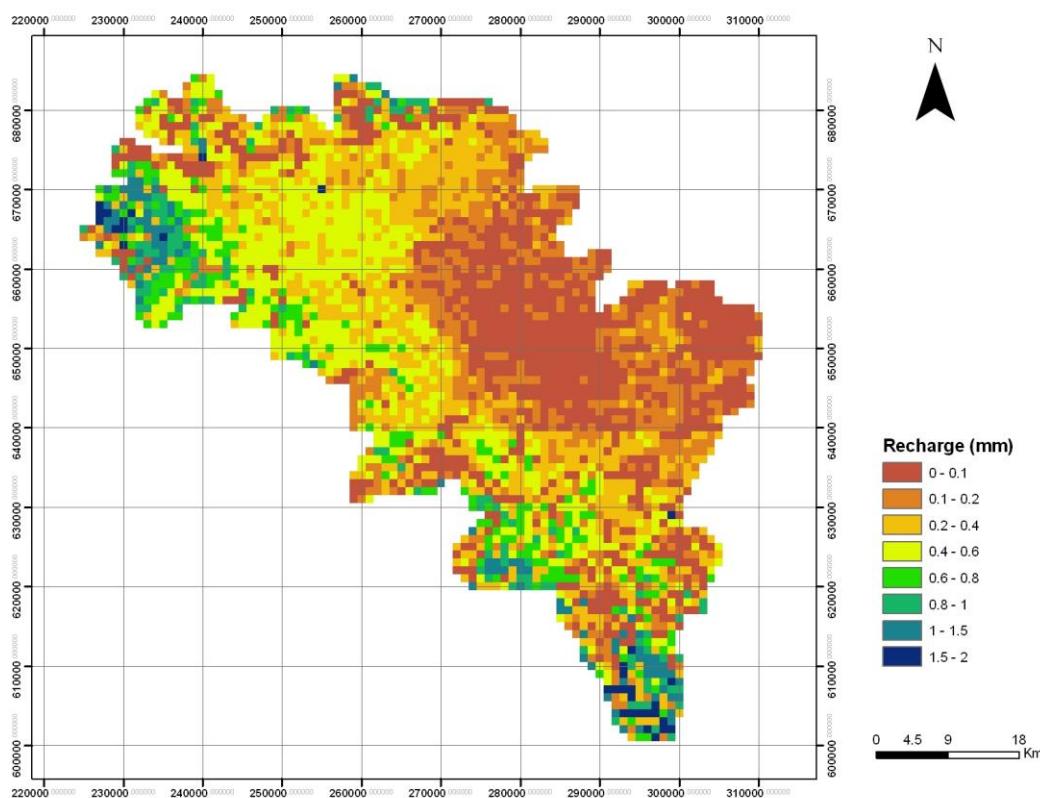


Figure 34. Calculated distributed long term average recharge from ZOODRM

4.3 STEADY STATE SIMULATION USING THE ZOOMQ3D GROUNDWATER FLOW MODEL

4.3.1 Model construction

The ZOOMQ3D groundwater flow model (Jackson and Spink, 2004) has been used to investigate aspects of groundwater flow in the superficial deposits in the Clyde Gateway area. As described earlier, however, a groundwater flow model has been set up to extend over a larger area than the Clyde Gateway, of approximately 370 km², covering most of Glasgow conurbation. The main channel of the River Clyde crosses the flow model from its southeastern to its northwestern corner. The extent of the model has been delineated based on the spread of the superficial deposits as defined by the DigMap coverage at 1:50,000 scale of the superficial deposits geology of the area (Figure 26).

The groundwater flow model for the superficial deposits comprises two layers (see Section 4.1.1). These are a high permeability layer at the top, resting on a lower layer. The lower layer has been subdivided laterally into two zones: one of moderate permeability and one of low permeability. The underlying Carboniferous bedrock forms a third layer in the model for the purposes of specific model runs to investigate the impact of the bedrock on groundwater flows within the superficial deposits (see Section 4.3.2).

A relatively fine grid mesh, with cell size of 40 m by 40 m, has been laid over the area surrounding the Clyde Gateway to allow refinement of the flow model (Figure 35). The fine mesh allows more detailed features to be included in the groundwater modelling. However, to reduce the run time of the numerical model and to improve its performance, this fine mesh is not maintained across the whole area of the groundwater flow model: across the rest of the model area the grid cell size is set to 200 m by 200 m (Figure 35).

There is no known groundwater abstraction from the superficial deposits within the groundwater flow model area. No abstraction has therefore been included in the model.

River locations have been taken from available maps. River stage relative to OD has been taken from a Digital Terrain Model (DTM) of the area, produced by the Centre for Ecology and Hydrology (CEH). Most of the rivers in the model are truncated by the model boundaries. Since these river branches originate from outside the flow model area, they carry river flows at their upstream ends against the model boundaries (Figure 35). The total river flows at these locations have been estimated from the surface flows calculated by the recharge model using baseflow indices. Since only steady state groundwater flow modelling runs have been undertaken, the long term average (LTA) surface flow values calculated by the recharge model have been used.

Gridded data representing recharge values are taken from the ZOODRM recharge model (Figure 34). The long term average gridded recharge values are used to undertake the steady state groundwater flow model runs. The application of these LTA recharge values is repeated over all the simulation stress periods.

Layer elevations and hydraulic conductivity values for the groundwater model have been exported from the GSI3D model using a new dedicated application that produces files which can be directly input to, and read by, ZOOMQ3D. This application transforms geological information from the GSI3D model (as illustrated in Figure 29) into files storing columns of lateral coordinate (X-Y) and attribute values. The attribute values are either the groundwater model layer (i.e. aquifer unit) elevations or the assigned hydraulic conductivity values. However, the GSI3D model does not cover the whole area of the groundwater flow model, which has necessitated the use of a utility tool prepared for ZOOMQ3D to extrapolate the hydrogeological layer elevation to the outer groundwater flow model boundary, and to convert the information into gridded data format.

The uppermost, high permeability model layer – Layer 1 – is assumed to be homogenous and is assigned a constant hydraulic conductivity value everywhere. It represents the higher permeability, largely sand and gravel-dominated geological units in the superficial deposits sequence, as illustrated by the blue layers in Figure 29. The lower model layer – Layer 2 – is subdivided into two different zones of hydraulic conductivity, both of which are lower than the value for the uppermost Layer 1. Zone 2 in Layer 2 has higher hydraulic conductivity than Zone 1 (Figure 36), representing the moderate permeability units within the superficial deposits sequence, which are typically dominated by fine sands. These are illustrated by the green layers in Figure 29. Zone 1 in Layer 2 has the lowest hydraulic conductivity value in the modelled superficial deposits aquifer, representing those units dominated by silts and clays in the sequence, as illustrated by the pink layers in Figure 29. A summary of the hydraulic conductivity values used in the model is given in Table 3. These were varied in the model runs, and the model results compared with available valuation data, in order to establish more confidence that the permeability values used were representative of actual values. The preferred final hydraulic conductivity values based on the results of the modelling are presented in Section 4.4.3.

The rivers simulated by the groundwater flow model are the River Clyde and its tributaries, and the major culverts within the Glasgow urban area (Figure 37). River stage values were derived from the Digital Terrain Model. The hydraulic conductivity of the river bed (the bed conductance), which controls the interaction between the aquifer and the river, is set to a constant value everywhere within the model. Several values for river conductance have been used during the calibration process of the model to investigate its impact on model results.

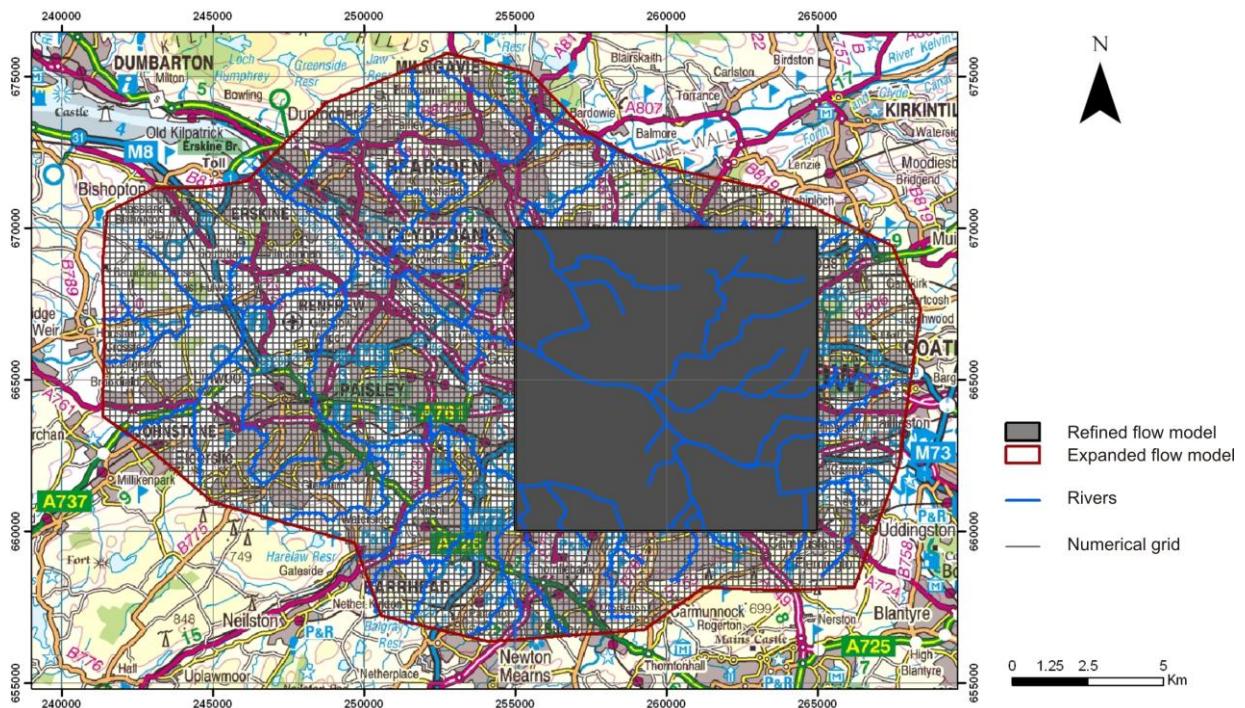


Figure 35. The extent of the ZOOMQ3D groundwater flow model, also showing modelled rivers and the area of increased grid refinement (OS topography © Crown Copyright. All rights reserved. 100017897/2009).

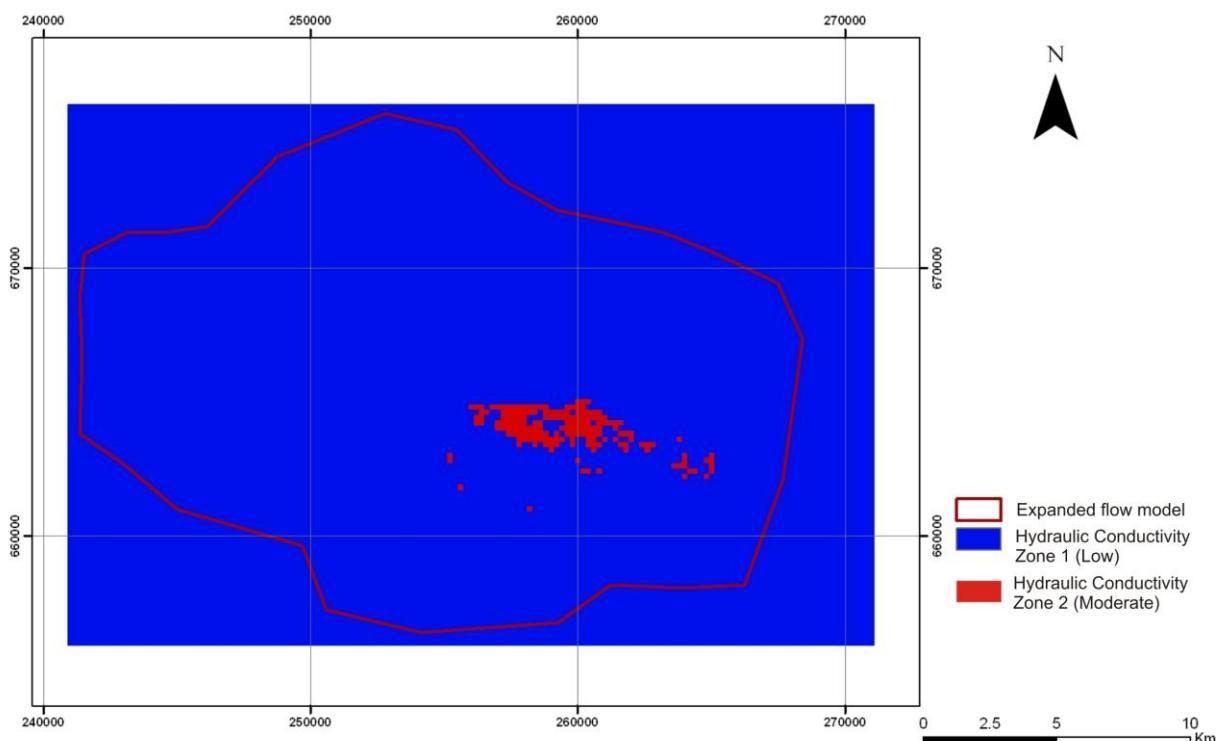


Figure 36. Hydraulic conductivity zones in Layer 2 of the groundwater flow model

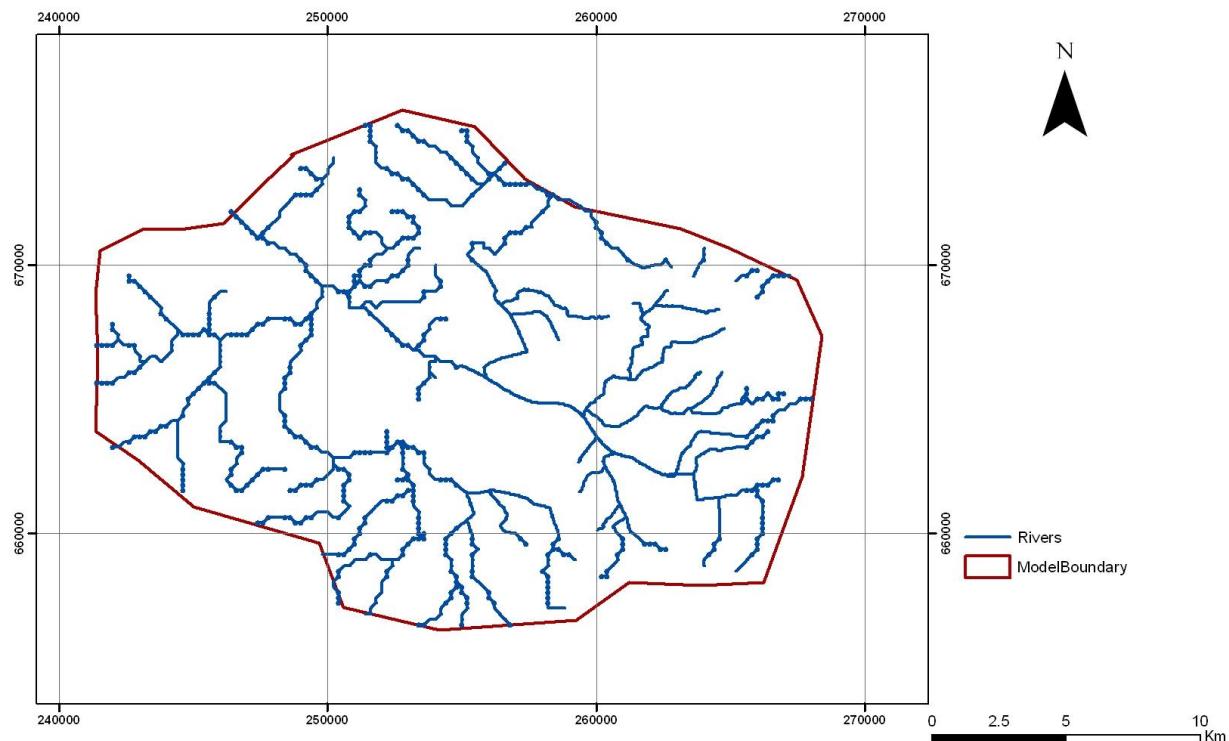


Figure 37. The River Clyde and its major tributaries, and the major culverts included in the groundwater flow model (all are modelled as ‘rivers’)

4.3.2 Calibration of the model and results

Available groundwater head (level) values from boreholes in the Clyde Gateway area have been used to calibrate the steady state groundwater flow model. Most of these values are in a zone along the line of the M74 extension; there are limited values elsewhere. Additionally, for most of the groundwater head data, there is no information about the depth at which the measured groundwater head relates to. The scarcity of groundwater head data, combined with the complexity of the groundwater system – the multi-layered aquifer horizons, each of which is likely to have different groundwater head characteristics, as described above – means that using these data for model calibration and validation is not straightforward. A detailed discussion of the issues surrounding the measurement and interpretation of groundwater level data is given in Ó Dochartaigh (2009). In summary, however, what this means is that it is not possible to directly associate the modelled groundwater head values with the available measured groundwater head data. The available groundwater head measurements can generally, therefore, only be used as an indicator of the accuracy of the groundwater flow model. However, there does need to be a consistent method of assessing the effects of changing model parameters on the model outputs, and for this reason, a quantitative method of assessing the improvement or deterioration of the modelled fit for each model run was used: this compared the squared differences between the simulated groundwater heads in the uppermost layer (Layer 1) and the available observed groundwater heads, calculated using values from 340 boreholes.

A total of seven model runs were undertaken to investigate the modelled groundwater system. Four runs were undertaken to investigate the possible distribution of hydraulic conductivity values in the two modelled superficial deposits aquifer layers. A fifth run was done to study the effect of including a third layer to represent the bedrock aquifer on the groundwater heads simulated within the superficial deposits. Two additional runs were done to investigate the effects of varying the river bed conductance value, which controls the river leakage portion of recharge, on the modelled groundwater heads.

In runs 1 to 4 and in runs 6 and 7, the model consisted of only two hydrogeological layers, representing the two superficial deposits aquifer layers as described above. In run 5, a third layer was added to represent the underlying bedrock aquifer.

The vertical conductance connecting the nodes between the model layers was calculated based on the thicknesses of the layers and on the assumption that the horizontal hydraulic conductivity value is three times the value of the vertical hydraulic conductivity (i.e., a ratio of horizontal to vertical hydraulic conductivity of three). This was done both between the two superficial deposits aquifer layers (Layer 1 and Layer 2) and between the lowermost superficial deposit aquifer layer and the underlying bedrock aquifer (Layer 2 and Layer 3) in run 5.

The parameter values used in the model runs are summarised in Table 3.

- **Run 1.** Layer 1 has a constant and higher hydraulic conductivity (10 m day^{-1}) and Layer 2 a constant and lower hydraulic conductivity (1 m day^{-1}). Layer 2 is not subdivided into moderate and low permeability zones in this run. The river bed conductance value was set to 1 m day^{-1} , and this was held constant for runs 2 to 5. The numerical results from this run are shown in Figure 38. There is good agreement between simulated and observed groundwater heads in the northeast of the model, but the simulated groundwater heads in the south and west of the model differ significantly from the observed. The sum of squared differences between the simulated groundwater heads in Layer 1 and the observed groundwater heads is 12754.
- **Run 2.** The hydraulic conductivity in both superficial deposits aquifer layers was increased: in Layer 1 from 10 m day^{-1} and in Layer 2, Zone 1 (low permeability zone) from 1 m day^{-1} . A moderate permeability zone (Zone 2) was also added to Layer 2, with a hydraulic conductivity value of 10 m day^{-1} . The simulated results are shown in Figure 39. The simulated hydraulic gradients are shallower than those produced from Run 1. This improves the agreement between the observed and simulated results towards the south and west of the model, but worsens the agreement in the northeast corner. The sum of squared differences between the observed and simulated groundwater heads is smaller than in Run 1, at 12225, indicating a generally better agreement between model and reality.
- **Run 3.** Again, the hydraulic conductivity in both superficial deposits aquifer layers was increased: in Layer 1 from 20 m day^{-1} ; in Layer 2, Zone 1 from 5 m day^{-1} ; and in Layer 2, Zone 2 from 10 m day^{-1} (Figure 40). The increase in modelled permeability throughout the aquifer layers improves the agreement between the simulated and observed groundwater heads even more than in Run 2 in the south and west of the model, but reduces the fit in the northeast (Figure 40). The sum of squared differences is larger than for Runs 1 and 2, at 18940, indicating that the modelled fit in general is worse.
- **Run 4.** This run reverted to the same hydraulic conductivity values used in Run 1 (Layer 1 – 10 m day^{-1} ; Layer 2 (Zone 1) – 1 m day^{-1}), but added a moderate permeability zone (Zone 2) to Layer 2 (5 m day^{-1}). The results were very similar to those produced in Run 1 (Figure 41). The sum of squared differences is 14830.
- **Run 5.** The hydraulic conductivity in Layer 1 was increased again to 20 m day^{-1} ; in Layer 2, Zone 1 it was increased to 5 m day^{-1} ; and in Layer 2, Zone 2 it was increased to 10 m day^{-1} . A third layer was added to represent the bedrock aquifer underlying the superficial deposits. The bedrock hydraulic conductivity was set to 0.5 m day^{-1} . Although this is a low value, the large thickness of this layer (over 180 m) results in a relatively high overall transmissivity for the layer. The resulting simulated groundwater heads (Figure 42) are similar to those from Run 3, where the hydraulic conductivity in the superficial deposits layers was set to relatively high values. The sum of squared differences between the simulated and observed groundwater heads is relatively large, at 18440.

- **Run 6.** This run investigated the effect of lowering the river bed conductance value. The hydraulic conductivity values were: Layer 1 – 20 m day⁻¹; Layer 2, Zone 1 – 1 m day⁻¹; and Layer 2, Zone 2 – 10 m day⁻¹. The river bed conductance value was reduced from 1 to 0.1 m day⁻¹. This resulted in steeper hydraulic gradients and made the agreement between the observed and simulated groundwater heads to the south and west of the model worse than the results from Run 1 (Figure 43). The sum of squared differences between the simulated and observed groundwater heads is the worst of all the runs, at 49200.
- **Run 7.** This run investigated the effect of increasing the river bed conductance value, to 10 m day⁻¹. The hydraulic conductivity values were the same as Run 6: Layer 1 – 20 m day⁻¹; Layer 2, Zone 1 – 1 m day⁻¹; and Layer 2, Zone 2 – 10 m day⁻¹. The modelled results are not significantly different from those of Run 1; however, the agreement between the observed and simulated results along the main channel of the River Clyde is improved (Figure 44). The sum of squared differences between the simulated and observed groundwater heads is the best of all the runs, at 10830.

Table 3 Summary of modelled aquifer parameters and output from each model run

| Run | Hydraulic Conductivity (m day ⁻¹) ¹ | | | River bed conductance (m day ⁻¹) | Sum of squared differences ² |
|----------|--|---------|---------|--|---|
| | Layer 1 | Layer 2 | Layer 3 | | |
| | | Zone 1 | Zone 2 | | |
| 1 | 10 | 1 | - | 1 | 12754 |
| 2 | 20 | 5 | 10 | 1 | 12225 |
| 3 | 50 | 10 | 20 | 1 | 18940 |
| 4 | 10 | 1 | 5 | 1 | 14830 |
| 5 | 20 | 5 | 10 | 0.5 | 18440 |
| 6 | 20 | 1 | 10 | 0.1 | 49200 |
| 7 | 20 | 1 | 10 | 10 | 10830 |

¹ To convert from m day⁻¹ to m sec⁻¹ multiply by 0.0000115. E.g. 1 m day⁻¹ = 1.15 x 10⁻⁵ m sec⁻¹; 10 m day⁻¹ = 1.15 x 10⁻⁴ m sec⁻¹; 50 m day⁻¹ = 5.75 x 10⁻⁴ m sec⁻¹

² Sum of squared differences between the simulated and observed groundwater heads for values from 340 boreholes

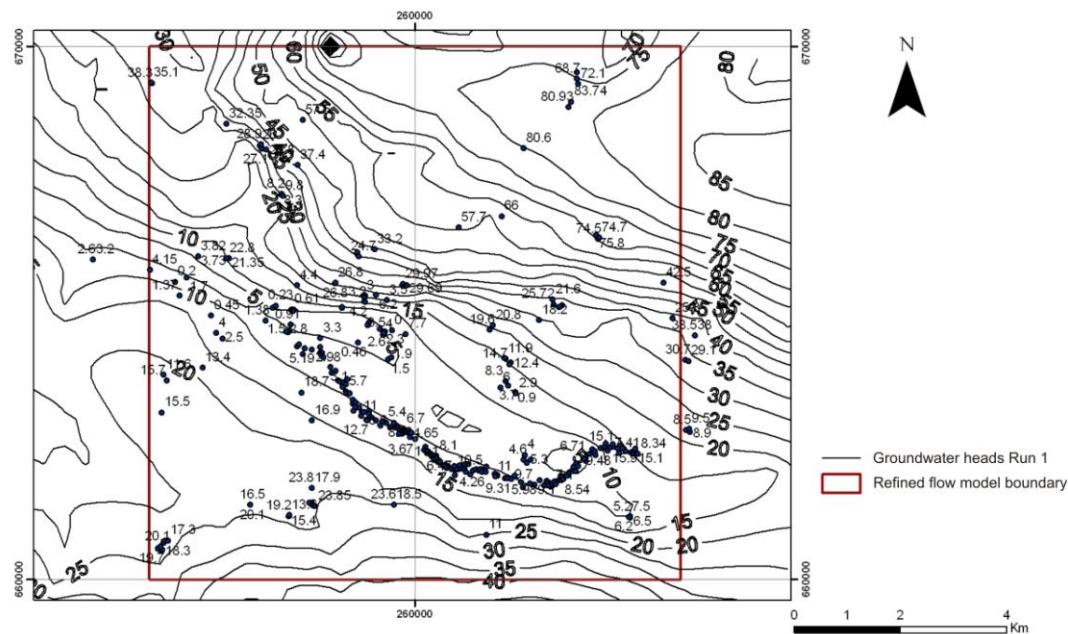


Figure 38. Run 1: simulated groundwater head contours (m AOD) plotted with observed groundwater level point measurements (m AOD)

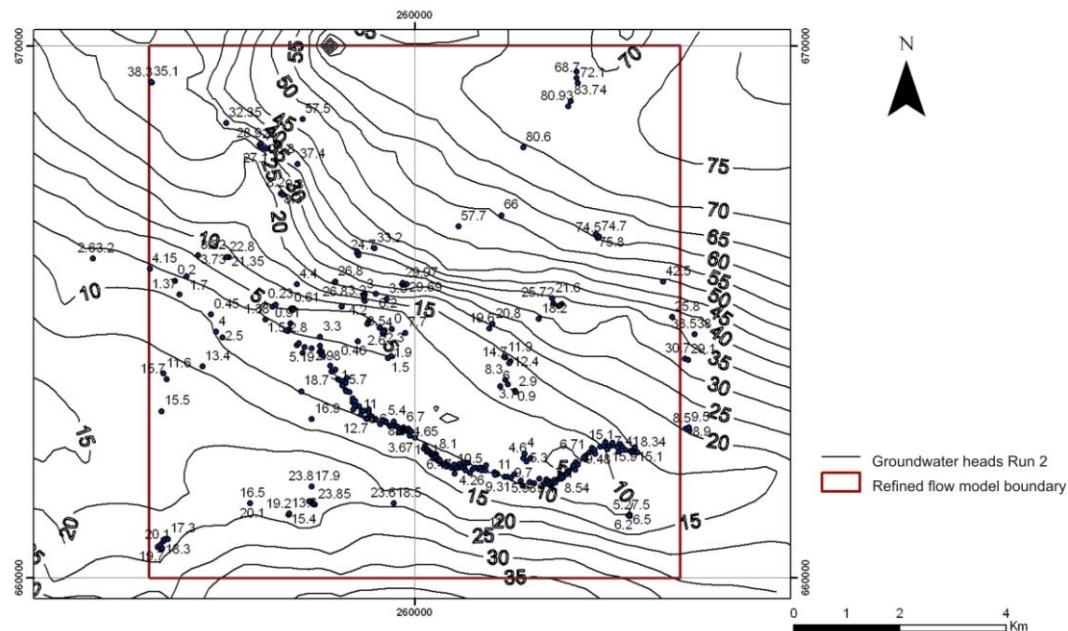


Figure 39. Run 2: simulated groundwater head contours (m AOD) plotted with observed groundwater level point measurements (m AOD)

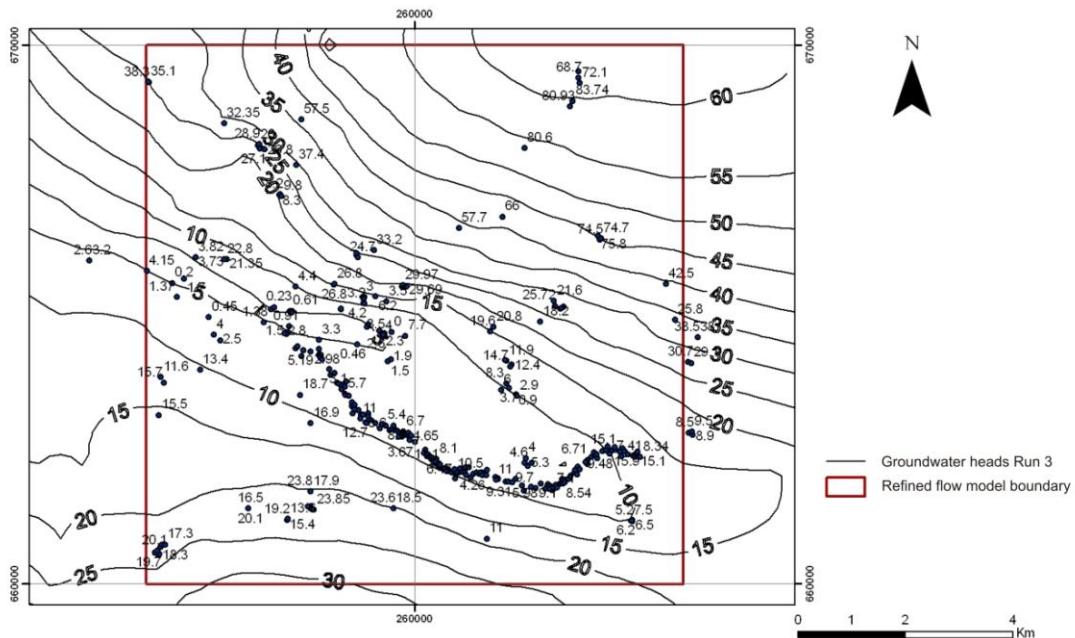


Figure 40. Run 3: simulated groundwater head contours (m AOD) plotted with observed groundwater level point measurements (m AOD)

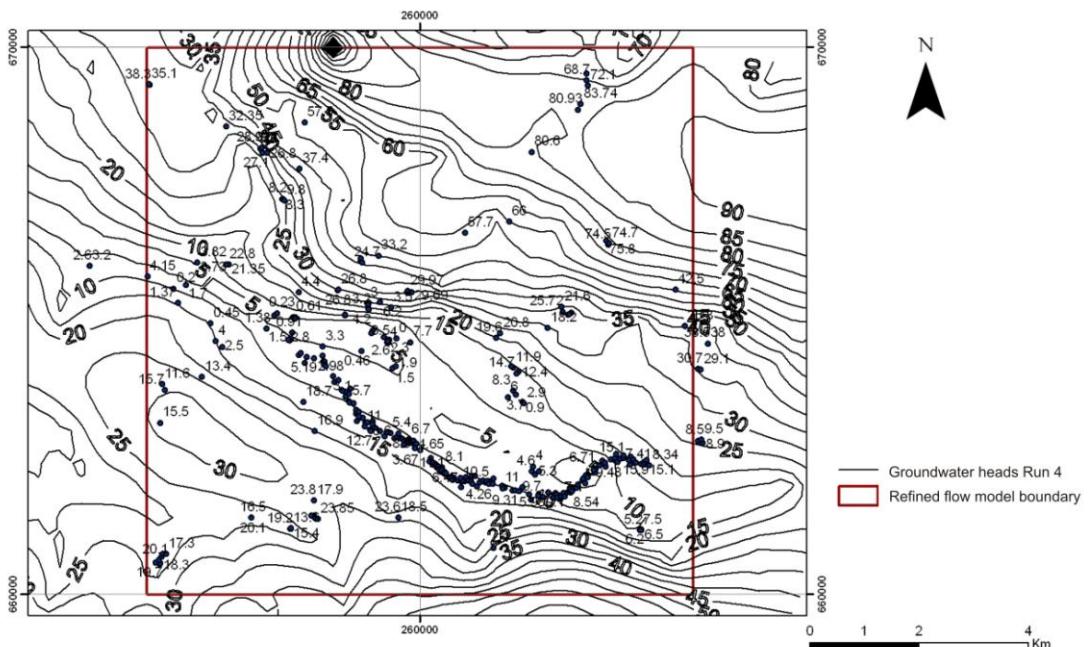


Figure 41. Run 4: simulated groundwater head contours (m AOD) plotted with observed groundwater level point measurements (m AOD)

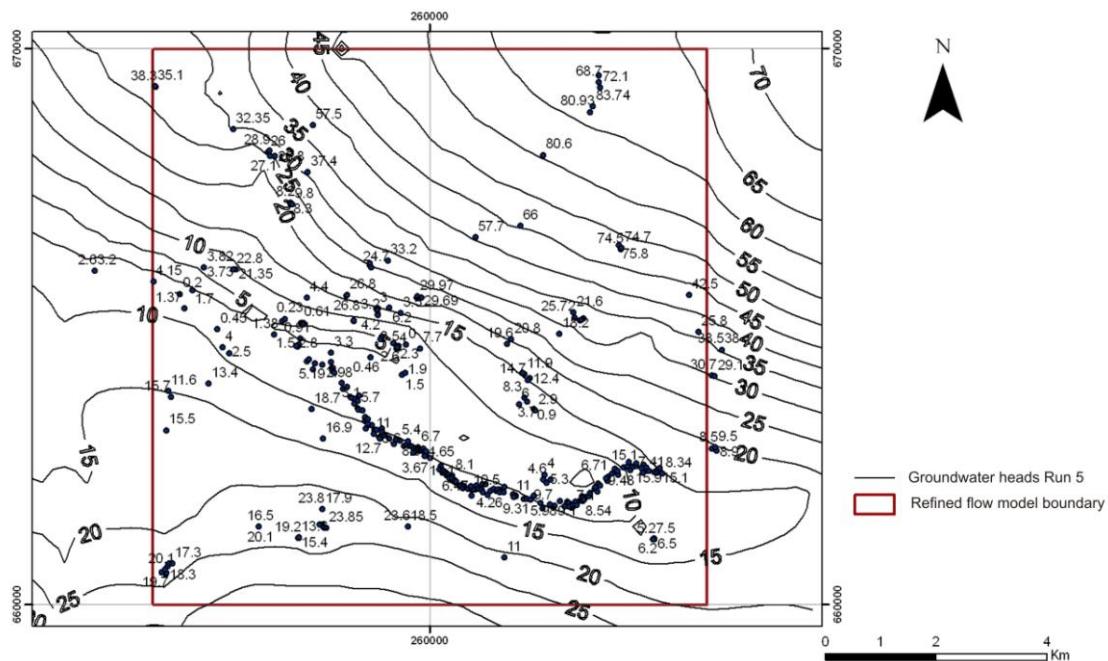


Figure 42. Run 5: simulated groundwater head contours (m AOD) plotted with observed groundwater level point measurements (m AOD)

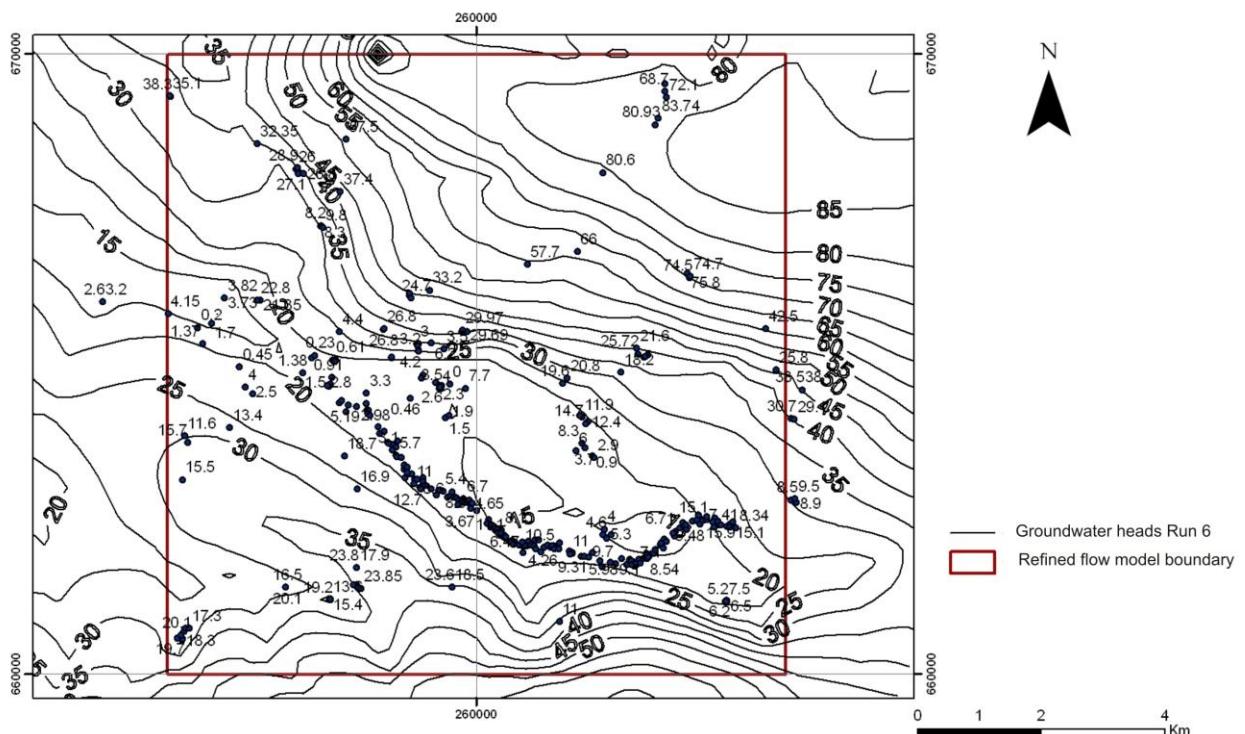


Figure 43. Run 6: simulated groundwater head contours (m AOD) plotted with observed groundwater level point measurements (m AOD)

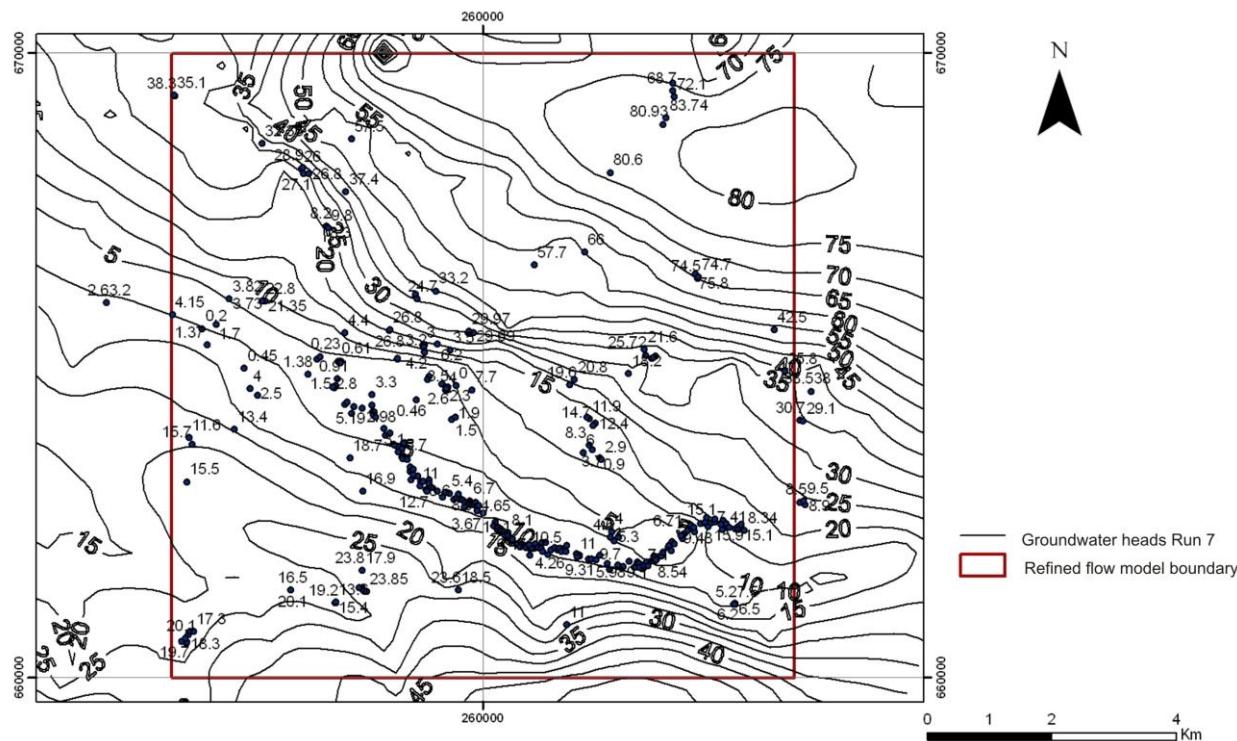


Figure 44. Run 7: simulated groundwater head contours (m AOD) plotted with observed groundwater level point measurements (m AOD)

4.4 SUMMARY AND RECOMMENDATIONS

4.4.1 Summary of groundwater model development

A steady state numerical groundwater model has been developed and seven model runs have been undertaken to simulate groundwater flow in the superficial deposits aquifers in the Clyde Gateway area of Glasgow. The geological structure of the groundwater model was based on the three-dimensional GSI3D geological modelling. The complexity of the superficial deposits structure and layering cannot be included in a groundwater model given the current availability of hydrogeological data. The superficial deposits layering was therefore simplified to produce two hydrogeological (aquifer) sub-horizontal layers, one of which was subdivided laterally into two permeability zones. A third layer, representing the underlying bedrock aquifer, was added for one model run.

Because GSI3D modelling focused on an area that is smaller than the groundwater flow model area, the top and base elevations of the hydrogeological (aquifer) layers were extended from the outer boundaries of the area with detailed geological modelling to the outer boundaries of the groundwater flow model using linear interpolation.

The distributed recharge model ZOODRM was used to estimate the long term average recharge values that were required as input to the steady state numerical groundwater flow model. A refined recharge calculation method has been developed and implemented to account for urban recharge. Major culverts and storm sewers were included in the model to improve the routing of surface water. Leakage from pressurised water mains was estimated based on available data on total water consumption, and added to the long term recharge values calculated within the urban area.

The groundwater flow model ZOOMQ3D was used to simulate groundwater flows. Calibration of the model was based on available measured borehole groundwater levels, most of which are restricted to a linear zone along the line of the M74 extension. The output from the groundwater

model was simulated groundwater heads over the modelled area. The simulated groundwater heads are controlled by the hydraulic aquifer parameters used in the model. In the absence of available data, these were largely estimated based on information from other similar hydrogeological environments.

Seven model runs were undertaken in order to better calibrate the model and improve the fit between simulated and observed groundwater heads.

4.4.2 Applicability of the groundwater model and recommendations for further work

The process of developing and running the model has highlighted a number of issues about the model itself, its sensitivity to the input parameters, and the relevance this has for making useful interpretations about the groundwater system in the Clyde Gateway area. These are summarised as follows:

- Surface water-groundwater interaction (the role of the rivers and the river bed conductance in the model) has a significant influence on the simulated groundwater heads. More work is needed to improve our understanding of this interaction and its effects.
- The simulated groundwater heads are influenced by the presence of the bedrock layer in model run 5, where the bedrock layer was introduced, because of its significant thickness. Further work is needed to improve our understanding of the hydraulic properties of the bedrock aquifer and to investigate its effects in the model on simulated groundwater flow and heads in the overlying superficial deposits.
- The model made a generalised assumption about the extent of the groundwater flow system. More work is needed to investigate how valid this assumption is.

The results from the modelling exercise highlight where further work is needed, to reduce the degree of uncertainty in the model and to improve the fit between the simulated and observed data. The most pressing issues are:

- The calculated recharge values should be improved by improving the way in which the model calculates surface flows to rivers and assesses leakage from pressurised water mains. In particular, more information on the mains water reticulation network would allow a better spatial distribution in the modelling of leakage from pressurised water mains. Better information on mains network leakage rates would also help to refine this aspect of the recharge model.
- The accuracy of the 3D geometry of the aquiferlayers (top and base elevation) in the groundwater flow model where it has been extended outside the area covered by the GSI3D model should be improved by better geological interpretation in these areas. The most effective approach to this would be to extend the GSI3D modelling over a wider area.
- The calibration process confirmed that the aquifer characteristics in the Clyde Gateway and wider Glasgow area are more complex than their representation in the conceptual and numerical groundwater model. The use of only two horizontal layers and three hydraulic conductivity categories is not enough to reflect the complexity of the heterogeneity of the superficial deposits. This should be addressed both by better geological interpretation outside the current area of the GSI3D model (as described above) and, particularly, by improved availability of hydraulic property data (including hydraulic conductivity and storativity) for the modelled aquifers. This latter will require aquifer testing (test pumping) in the different aquifer units, in order to derive new, high quality hydraulic parameter data.
- More numerical simulations are required to estimate the values of the hydraulic parameters of the aquifer. If the number of permeability classes is increased, Monte Carlo simulations could be used to estimate the best values of the hydraulic parameters of these classes. This also helps estimating the uncertainty associated with the values given to these parameters.

- Additional monitoring of groundwater levels is required to fill the gaps where no data are currently available and to improve the quality of the available data, particularly related to the variability in groundwater level data with depth in the multi-layered aquifer, and to their variability over time.

4.4.3 Model-based interpretation of the groundwater system in the Clyde Gateway

The groundwater model has confirmed the general conceptual model of the groundwater system in the Clyde Gateway area. The overall direction of modelled groundwater flow is down-gradient from areas of higher elevation towards the River Clyde, and appears to be controlled both by topography and by the position of the River Clyde, and by its larger tributaries.

Modelled groundwater levels are typically shallow beneath the low elevation land adjacent to the River Clyde. They are not necessarily deeper beneath higher ground: in many areas, the model quite closely reproduces relatively shallow (less than 5 mbgl) groundwater levels in areas where the observed water levels are also shallow.

That the overall pattern of simulated groundwater heads fits relatively well with the available observed data across much of the modelled area. This indicates that the general distribution of the modelled aquifer layers and their relative hydraulic properties are reasonable assumptions. Based on the model run outputs, the higher permeability uppermost aquifer layer (Layer 1) is likely to have an average hydraulic conductivity of around 20 m day^{-1} ; the moderate permeability aquifer (Zone 2 in Layer 2) is likely to have an average hydraulic conductivity of between approximately 5 and 10 m day^{-1} ; and the low permeability layer (Zone 1 in Layer 2) is likely to have a hydraulic conductivity of between 1 and 5 m day^{-1} .

The model runs indicate that average river conductance may be around 10 m day^{-1} or possibly higher, but further runs would be needed to be more conclusive about this.

What the model cannot yet adequately represent, which is of great importance, is the full heterogeneity in the system. Using a single river bed conductance value across the whole modelled area, for example, is likely to be a gross simplification. Similarly, there is likely to be much small-scale variation in the permeability of each of the aquifer layers that is not represented by the single value used in the model.

4.4.4 Conclusions

The groundwater model has successfully reproduced, albeit at a coarse scale, the major known features of the groundwater system in the Clyde Gateway area, confirming the general picture of our conceptual model of the system. However, it should be remembered that it is only the first step in a process of developing a full, robust time-variant groundwater model for the Clyde Gateway area. As it stands it provides a reasonably good – and certainly the best available – simulation of the groundwater system, but it is based on sparse data and a lot of assumptions. Crucially, it highlights where more data are needed to develop the model further and hence improve its robustness and the confidence with which we can apply results from the model to different scenarios and at different levels of detail. The groundwater model should therefore be seen as a platform for refinement and future exploitation, rather than a final product in its own right. As it stands, however, the initial investment into a preliminary groundwater model represents an excellent opportunity for enhancing the application of the 3D geological modelling. The model also has potentially widespread relevance to the river basin management planning currently being carried out by SEPA under the direction of the EU Water Framework Directive.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: <http://geolib.bgs.ac.uk>.

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Appendix 1

Subsurface Viewer User Manual

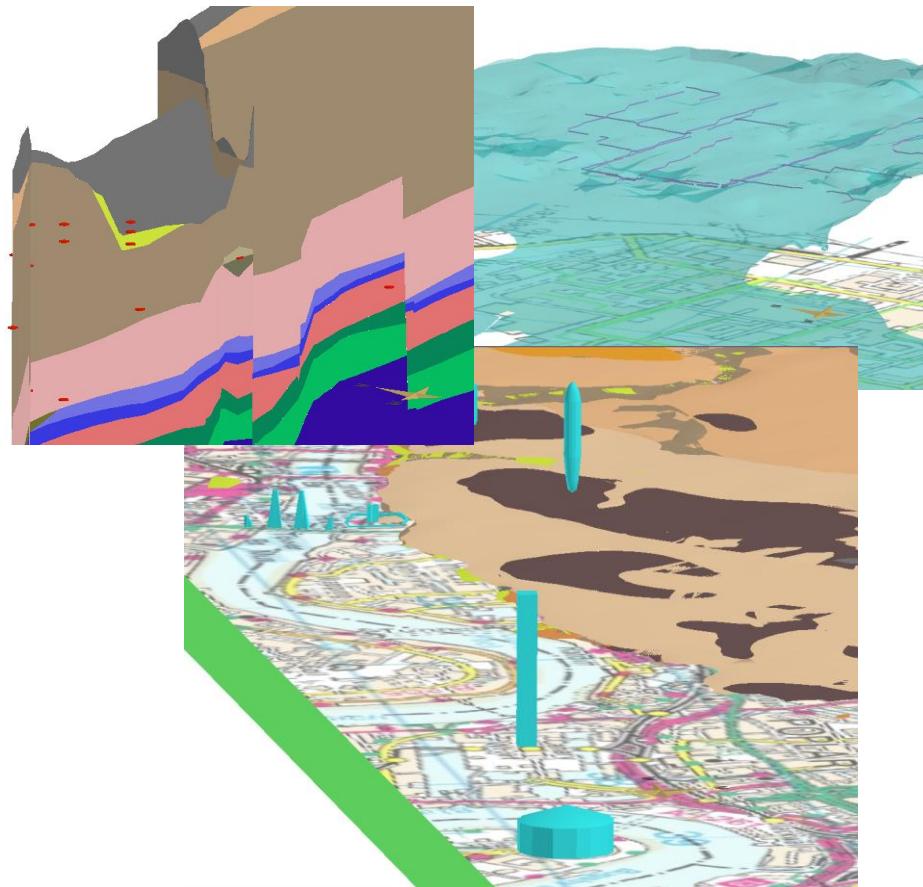


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Subsurface Viewer 2009: User Manual V1.0

Geological Modelling Systems Team
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Geological Modelling Systems Team
OPEN REPORT OR/09/027

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Keywords

3 dimensional geological models
Subsurface, Viewer, Geology,
Synthetic cross-sections, slices &
boreholes

Front cover

Snapshots of Subsurface Viewer model outputs showing synthetic cross-sections in 3D with water strikes, sewerage pipes embedded in till and buildings on top of bedrock in London.
Exploded Chichester Model as front piece.

Bibliographical reference

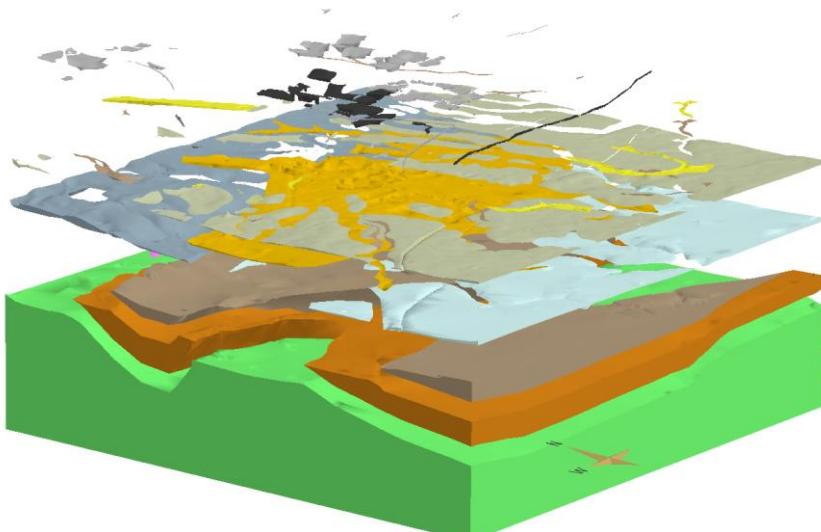
TERRINGTON, R, L, MAHTERS, S.
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VIEWER 2009: USER MANUAL
V1_0.2010. *British Geological
Survey Open Report, OR/09/027.*
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Maps and diagrams in this book use topography based on Ordnance Survey mapping.

Subsurface Viewer 2009: User Manual V1.0

R. L. Terrington, S. J. Mathers, H. Kessler, V. Hulland & S. J. Price



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Foreword

This user manual is the published product by the British Geological Survey (BGS) for the instruction of using the Subsurface Viewer.

Acknowledgements

This user-manual has been written by Ricky Terrington in collaboration with Steve Mathers and Holger Kessler. The Subsurface Viewer was developed by INSIGHT Geologische Softwaresysteme GmbH in 2004/2005 for the visualisation and analysis of digital geoscientific spatial models. To date over 20 geological models have been packaged in the Subsurface Viewer. These geological models have been published through the GSI3D Geological Surveying and Investigation in 3D (GSI3D) software also developed by INSIGHT.

We would also like to thank Camilla Taylor for testing the usability of the Subsurface Viewer and the improvements made on the manual.

This user-guide is intended for geoscientists and geological enthusiasts in BGS, and elsewhere, for using the software and methodology to view 3D geological models in the Subsurface Viewer.

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Summary

This user guide describes the tools and methodology for investigating and analysing 3D geological models using the Subsurface Viewer.

5 Introduction

The Subsurface Viewer is an exciting new package developed by INSIGHT Geologische Softwaresysteme GmbH for the visualisation and analysis of digital geoscientific spatial models. This Viewer has been developed following the popularity of INSIGHT's Geological Surveying and Investigation in 3D (GSI3D) software tool that BGS uses extensively for the construction of systematic near surface models (Kessler and Mathers, 2004; Kessler *et al*, 2005; Kessler *et al*, 2009).

Geological Models are embedded within the Subsurface Viewer as the means of publication. In this way the constructed model can be examined and analysed to produce:

- Models displaying the geology or other pre-selected applied themes (e.g. hydrogeological properties)
- Geological maps (at surface and uncovered)
- User defined synthetic borehole logs
- User defined horizontal slices and vertical sections
- Visualisation of the geometry of single and combined units

Please note that the models supplied with the Subsurface Viewer are encrypted and cannot be altered, nor can users add additional data.

6 Installation and use of the Subsurface Viewer

The model and the necessary Java software and extensions will be delivered to the client on a CD-ROM or via a secure FTP site.

The executable file will install java software onto the PC if the minimum Java Runtime is not found, so administrative permissions must be set accordingly.

To load the Subsurface Viewer onto your computer, double click the executable (*setup.exe*) with the following icon



The executable will have a prefix of the model contained within the Subsurface Viewer. Follow the instructions that will include

- Licence Agreement
- Location of the folder for which the Subsurface Viewer will be installed
- ReadMe file which contains important information about the setup and how to get support

Press ‘Finish’ to complete the process and load the Subsurface Viewer on your computer.

Once installed, the “*model*”.exe will appear as a short cut on your desktop view and will have the following icon.



The model can also be run from **Start>Programs>Subsurface Viewer>“Model Name”** and clicking the “*model*”.exe if preferred.

To **un-install** or **change** installation settings of the Subsurface Viewer, click on the original *setup.exe* with the icon and follow the instructions.



Each unique model is supplied with its own inbuilt version of the Subsurface Viewer and a licence. This means that the software is not a stand-alone package but is an integral part of each published model.

6.1 TECHNICAL SPECIFICATION FOR USE OF THE SUBSURFACE VIEWER

The following are the recommended **minimum hardware requirements** for using the Subsurface Viewer

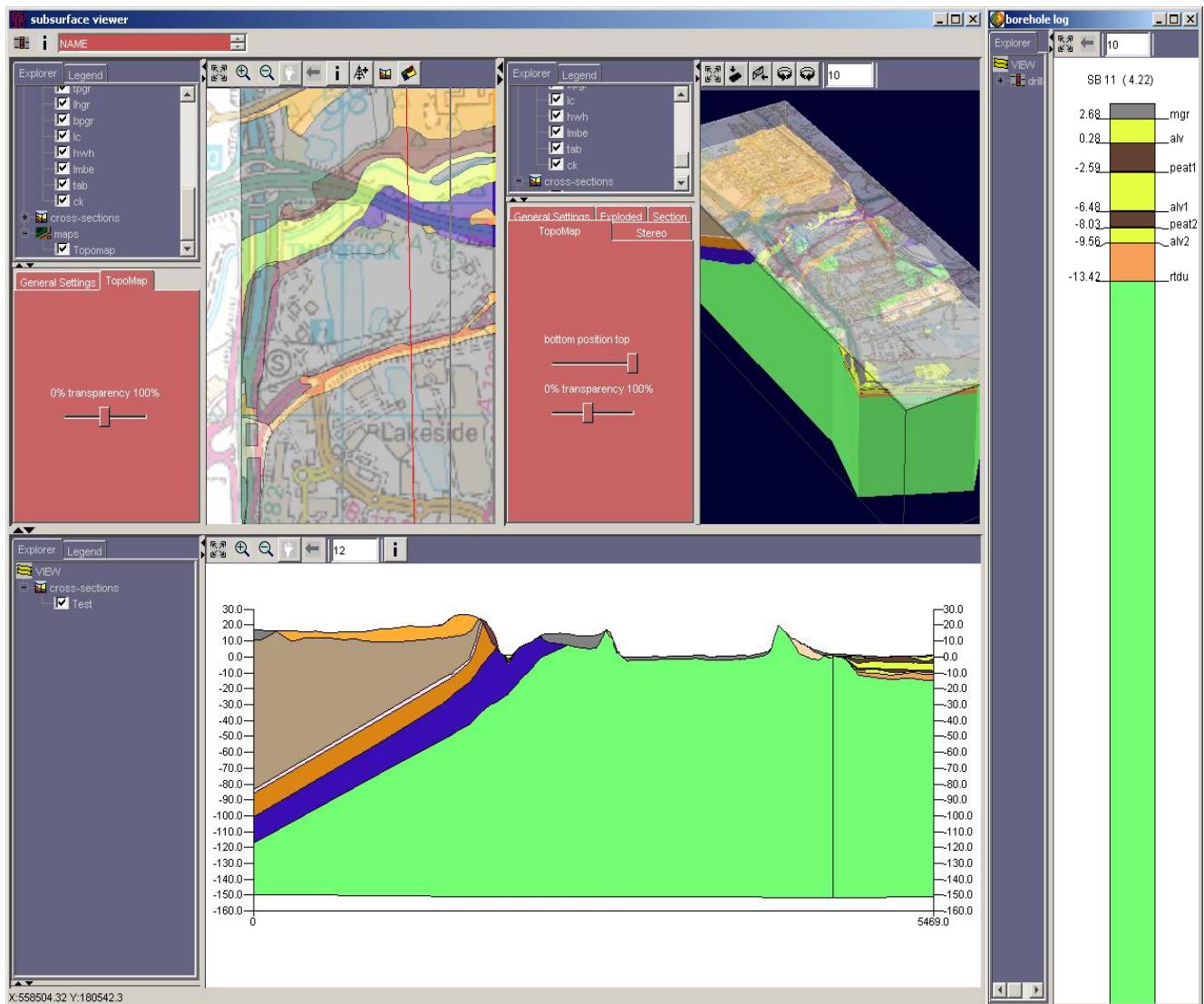
- PC running Microsoft Windows 2000/XP or Windows XP 32-bit editions only
- Either Intel Pentium family 32/64 bit processor 1GHz+ or AMD Athlon family 32/64 bit Processor 1GHz+
- **Minimum** of 256Mb of system RAM. Larger models will need 512Mb or more.
- A PC desktop graphics card using either Nvidia Geforce, Nvidia Quadro or ATI Radeon chipsets with minimum of 64Mb video RAM (**Other makes of card may be supported including those in laptops**).
- 120Mb of Hard disk for the Java + Viewer installation. (1 Mb required for Viewer only installation)

If you have any queries or problems installing or using the Subsurface Viewer please contact our enquiry team on enquiries@bgs.ac.uk or Tel: 0115 9363143

7 Viewer Interface

Note in this manual **<Lmb>** and **<Rmb>** are used for left and right mouse button clicks respectively

The Subsurface Viewer contains 4 windows for the visualisation of the model as shown below. These are clockwise from top left the Map, 3D, Synthetic borehole log, and Synthetic section windows



On loading the model is automatically displayed in the Map Window and the 3D Window. The Synthetic-section Window is empty until a synthetic section is drawn. The Synthetic-borehole log Window needs to be activated separately by clicking on the borehole icon (shown below) in the top left corner of the header bar and then resized.



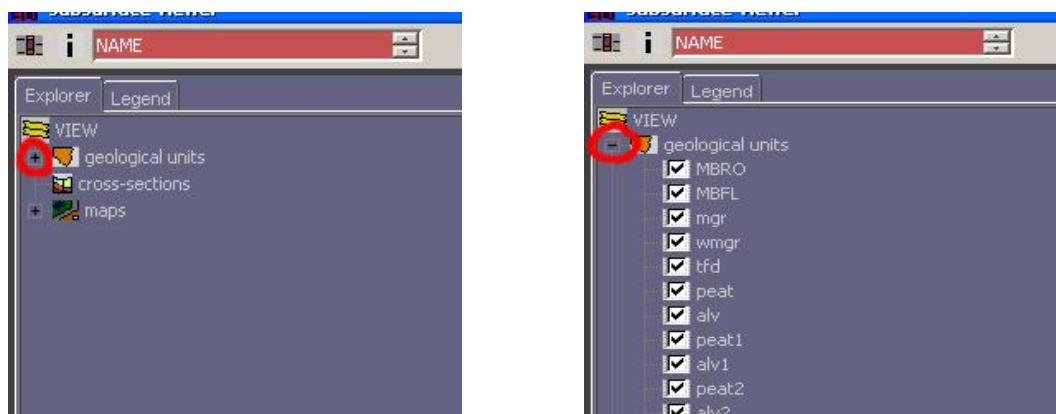


Information Tool. <Lmb> provides information about the software owner

The **NAME** menu indicates what attribute of the model is being displayed. By simply toggling the up and down arrows and clicking once on the attribute, a new attribute will be defined in the Map, 3D and Synthetic-section windows.

The **Explorer** tab in all windows opens the table of contents whereas the **Legend** tab reveals the colour key to the geological units in each of the three main windows.

- The layers that make up the model can be viewed by double clicking the left mouse button <Lmb> on . Use to drill down the layers and the to zip the layers back up.



- **X** and **Y** coordinates can be viewed in the bottom left of the interface when the cursor is placed in the Map (**Note – coordinates only appear when all maps in both the Map and 3D windows have been turned off**). Additionally, a **Z** (depth in metres) value can be obtained when a synthetic cross-section has been drawn and the cursor is placed in the Synthetic-section Window.

Dragging the border or using the arrows shown below can resize all the windows and tab boxes.



7.1 THE MAP WINDOW:

The Map Window enables the view of geological units in 2D, individually or collectively, from above or below, as coverage's or contoured bases and tops. The Map Window can also display topographic raster maps for reference, or maps indicating the uncertainty of the model.

In the Map Window the user can specify the alignment of synthetic cross-sections and the location of synthetic boreholes.

Tools include:



Zoom to full extent. $<Lmb>$ click once on tool to use.



Zoom in. $<Lmb>$ click on tool. Hold down $<Lmb>$ and stretch over an area of interest in the Map Window. Release $<Lmb>$ once area has been defined.



Zoom out. Click on tool once with $<Lmb>$ to zoom out. Continue clicking until a desired view is obtained.



Pan. $<Lmb>$ click on tool. Hold down $<Lmb>$ in Map Window to drag map/model across screen. Release $<Lmb>$ to reveal new position of map/model.



Information tool. $<Lmb>$ click. Provides information about software owner.



Previous View. $<Lmb>$ click to go back to previous view.



Synthetic borehole. Use $<Lmb>$ on tool. Click once with $<Lmb>$ at location in the Map Window where the synthetic borehole is required. Go to the Synthetic borehole log window (Section 3.4) for further details about viewing the synthetic borehole.



Synthetic cross-section. Use $<Lmb>$ on tool. Click once with $<Lmb>$ on Map Window. A line will appear from where the mouse was clicked on the Map Window. This will show where the cross-section will be drawn. A double-click on the $<Lmb>$ will complete the cross-section and red line will appear showing the location. A synthetic section can be constructed by using as many points as required, providing there are at least two. A window will also materialize asking for the new cross-section to be named. Once named the section appears in the Synthetic-section Window. Go to the Synthetic-section Window (Section 3.2) for further details.



Synthetic Horizontal Slice. *<Lmb>* click will bring up a message box asking the user for a depth at which the 3D model will be sliced to relative to Ordnance Datum (OD). For example, if the user specified a depth of 5m, the model in the map window would have the ground above this height removed, leaving only geological units that occur at this OD in the map window view. (**Note - As the 3D model incorporates ground above and below sea level, the depth of the slice will be an absolute value, where mean sea level is taken as 0**).

This map, created from taking the horizontal slice, is held in the “maps” drop down menu under “View” in the “Explorer” tab. To return to the original view un-tick the box for the slice, as shown below.

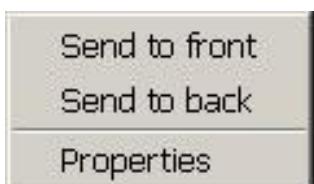


The map currently selected (HS-0) refers to a horizontal slice cut at 0m above mean sea level. (HS-10 and HS--10 refer to slices 10m above and 10m below the mean sea level, respectively).

In the side menu bar, under the “Explorer” tab *<Lmb>* click on “View” to display the **geological units, cross-sections or maps** and this will reveal the following self-explanatory options:



Then, having drilled down the options using the + button, *<Rmb>* click on any individual **geological unit, cross-section or map** to reveal two self-explanatory “send to” options plus Properties – *<Lmb>* click on Properties to reveal the **Object** tab discussed below.

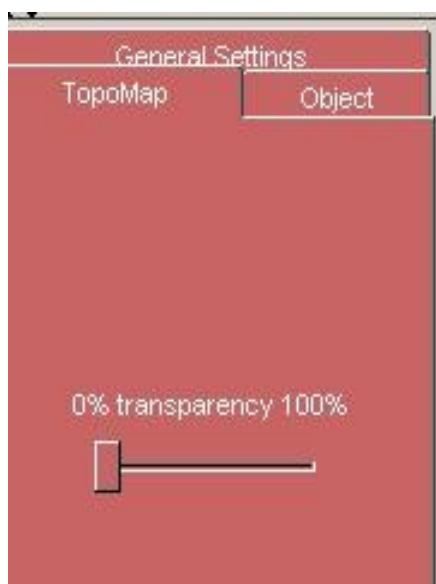


<Lmb> on the **General Settings** tab reveals the screen below. Here the user can define the background colour from a palette by *<Lmb>* on the white rectangle. Also the frame and cross-

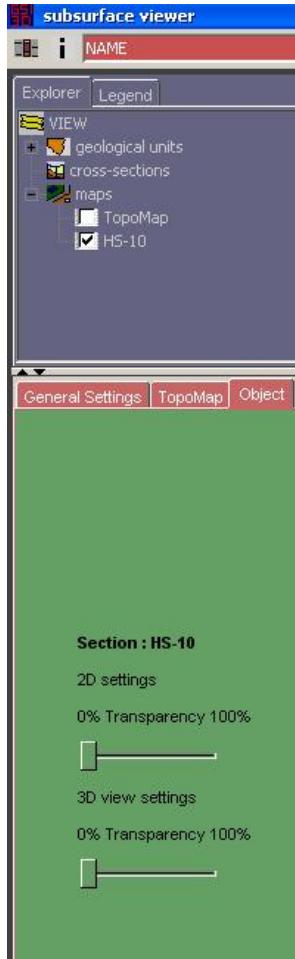
hairs can be toggled on and off. $<Lmb>$ on the save map icon gives the option to save the current view as a *.png, with a user defined metre to pixel ratio (N/B future versions will enable scaled printing)



$<Lmb>$ on the **TopoMap** tab opens up the following screen. The slider bar allows seamless setting of transparency in the Map Window.



Properties of other maps (not named TopoMap in the “maps” drill down menu) need to be controlled by <Rmb> on the map and then transparency can be adjusted in the “Object” tab, as shown below.



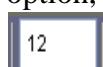
<Rmb> on a **Geological Unit**>**Properties** reveals the **Object** tab shown right. The name or code of the selected unit is displayed in bold at the top. Select whether to contour the base or top of the unit and set the preferred contouring interval in metres. The unit is shown in its pre-determined colour when the **extent of unit** is ticked on. The slider bar immediately below varies the transparency. The **3D view settings** give the option to display the geological units in one or more ways. These can be floating **contours**, a triangulated **mesh** or colour **shaded** objects. The bottom slider bar varies the transparency of the 3D colour shaded object.



7.2 THE SYNTHETIC-SECTION WINDOW:

Note – The Synthetic-section Window is only active once synthetic cross-sections have been selected in the Map Window using the **synthetic cross-section** tool.

The tool icons on the header bar of the Synthetic-section Window are identical to the Map Window.

There is one additional option, which is to specify the vertical exaggeration by typing the value in the box shown here: 

The vertical exaggeration has to be selected by the user to display each model. Typical values however are between 5 and 25.

As for the Map Window, the **Explorer** tab reveals the Table of Contents whilst the **Legend** tab displays the units present in the section(s).

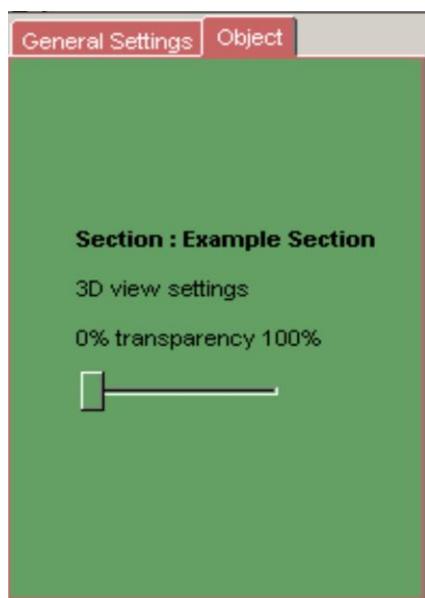


<Rmb> click on the **General Settings** tab reveals the screen below. Here the user can define the background colour from a palette by <Lmb> on the white rectangle. Also ticking the scale box creates a scaled frame surrounding the synthetic section.

<Lmb> on the save map icon gives the option to save the current view as a *.png, with a user defined metre to pixel ratio



<Rmb> click on any synthetic section in the table of contents enables the user to set the properties of the section using the screen below. The name of the section is shown in bold at the top of the screen. By ticking the labelling box the section can be labelled with the names of the geological units. The slider bar varies the transparency of the section in the 3D window.



Note: To view multiple synthetic cross-sections at the same time go to the **3D Window** (Section 3.3)

7.3 THE 3D WINDOW:

The 3D Window enables interactive viewing of the model and uses the left and right mouse buttons for all navigation.

Rotate model - Hold down the $<Lmb>$ on the 3D Window and move the mouse until you reach the required angle. Release $<Lmb>$ to halt rotation.

Zoom in/out – Hold down the $<Rmb>$, move the mouse in an upward direction to zoom out and a downward direction to zoom in. Release $<Rmb>$ to halt zoom.

Pan – Hold down both buttons and move mouse in any direction to pan the model.

Additional tools in the header bar of the 3D Window include:



Spin model clockwise – Click once to start (button will then appear black), click again to switch off.



Spin model anticlockwise – Same as above



Vertical/plan view of model



Horizontal view of model

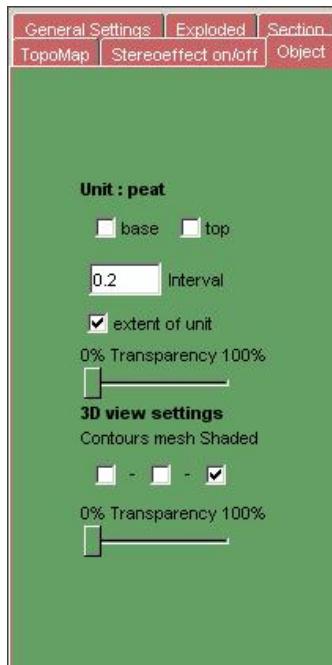
$<Rmb>$ click (on geological properties) followed by $<Lmb>$ click will give the following self-explanatory options: –

1. Hide all objects
2. Show all objects

Alternatively, each unit can be switched on or off individually by clicking on the tick as previously mentioned in the Map Window (Section 3.1).

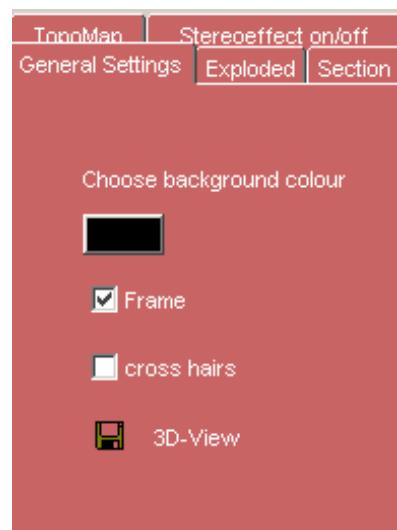
$<Rmb>$ on an individual unit gives the option to display the properties screen by $<Lmb>$ on Properties shown below

This content window is identical to that shown above in the Map Window (Section 3.1).



The menu tabs

<Lmb> on the **General Settings** tab gives the following screen



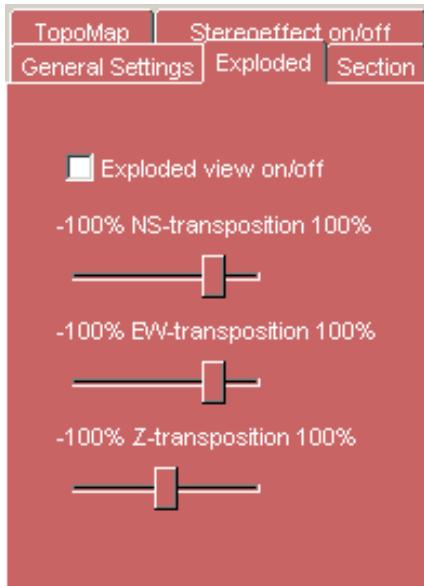
Background colour – <Lmb> brings up a screen to select background colour from palette

Frame – Toggles the frame on/off in 3D Window

Cross-hairs – Toggles the cross hairs on/off in 3D Window

3D-View – <Lmb> on the save icon gives the option to save the current view as a *.png, with a user defined metre to pixel ratio

<Lmb> on the **Exploded** tab gives the following screen



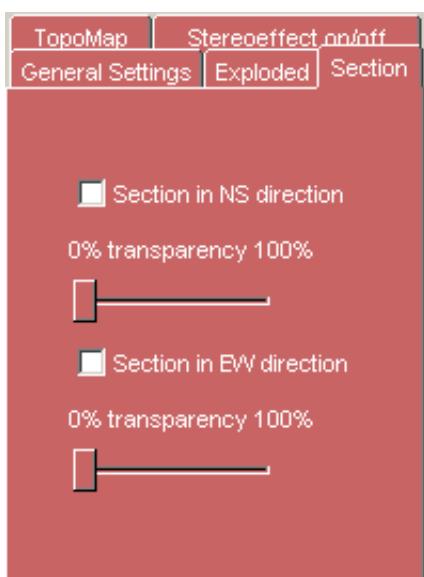
Exploded view on/off toggles the explosion of model on/off, i.e. the separation of individual geological units from other geological units.

NS-transposition – use slider bar to explode model in a north/south direction.

EW- transposition – use slider bar to explode model in an east/west direction.

Z- transposition – use slider bar to explode model in a vertical direction.

<Lmb> on the **Section** tab gives the following screen

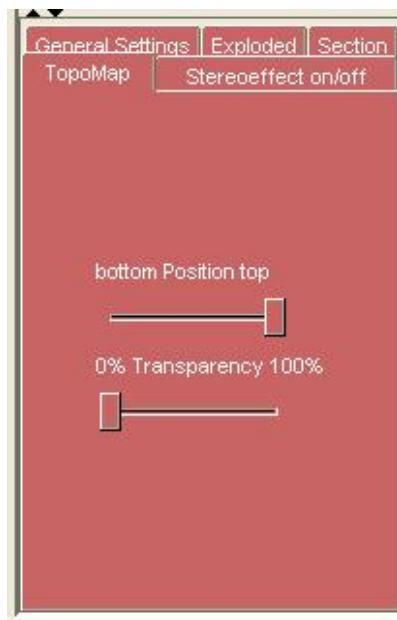


Note - Hide all geological objects to view vertical slices. Adjusting the transparency of the topological map also aids visualisation of these slices.

Section in NS-direction– tick on and then move mouse across Map Window screen to view vertical slices of the model in a north/south direction

Section in EW-direction– tick on and then move mouse across Map Window to view vertical slices of the model in an east/west direction

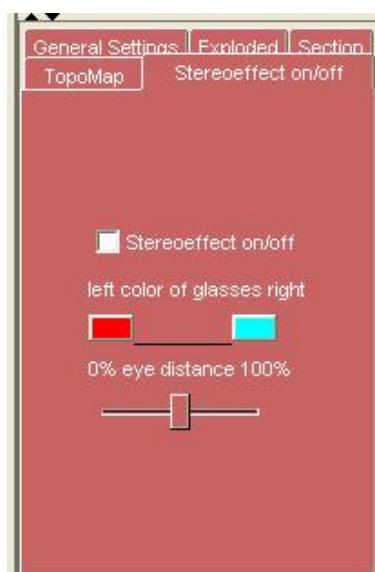
<Lmb> on the **TopoMap** tab to open the following screen



bottom Position top – Sets topographical position relative to model using slide bar.

Transparency – use slide bar to set transparency of topographical map.

<Lmb> on the **Stereoeffect on/off** tab gives the following screen



Stereoeffect on/off – View model in 3D stereo.

color of glasses – sets colours to match colour of 3D glasses.

eye distance – use slider bar to adjust

7.4 THE SYNTHETIC-BOREHOLE LOG WINDOW:

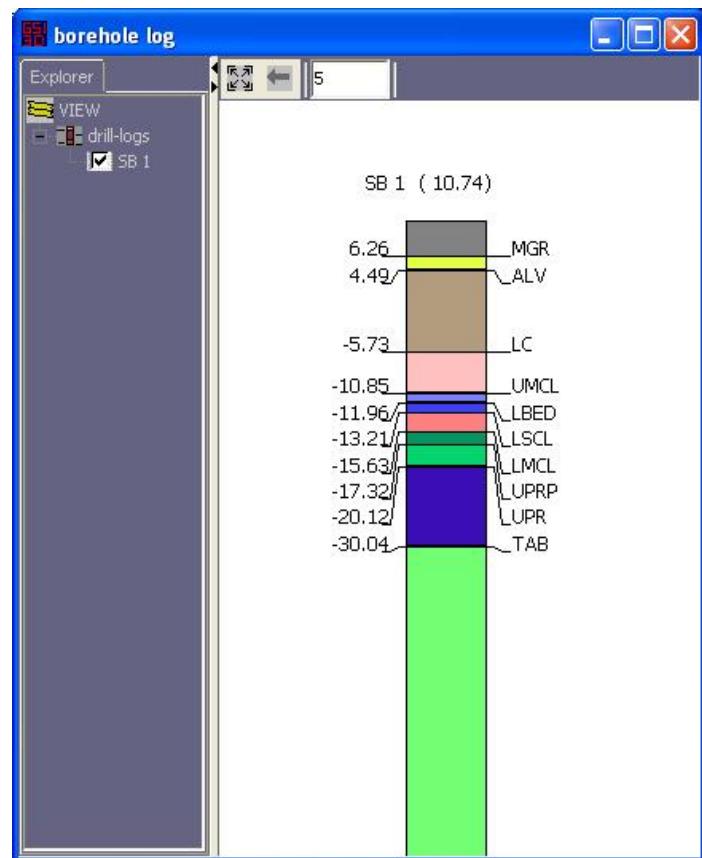
Once the synthetic borehole viewer tool has been used on the Map Window,

click on  in the top right hand corner which will open up the borehole viewer screen (shown below).

The tools in the borehole viewer screen carry the same functionality as the tools in the Map and Section windows. However, to pan hold down the *<Lmb>* to drag the borehole stick to the desired location in the display.

The borehole viewer display also shows:

- The depth to the base of each geological unit relative to OD.
- The OD and name of the synthetic borehole at top
- The name of each of the units modelled is attached to their base.



References

Kessler, H. & S.J. Mathers. 2004. Maps to Models. *Geoscientist*, 14/10, pp. 4-6.
<http://www.bgs.ac.uk/science/3Dmodelling/mapstomodels.html>

Kessler, H. et al. 2005. 3D geoscience models and their delivery to customers. In: Three dimensional geologic mapping for groundwater applications, Workshop extended abstracts, Salt Lake City, Utah, 15 October 2005. Geological Survey of Canada, 2005. p. 39-42.
<http://crystal.isgs.uiuc.edu/research/3DWorkshop/2005/pdf-files/kessler2005.pdf>

Kessler, H., Mathers, S.J. & H.-G. Sobisch. 2009. The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology. *Computers & Geosciences*, **35**, 1311–1321.

<http://dx.doi.org/10.1016/j.cageo.2008.04.005>

Glossary

Borehole Log A synthetic borehole drilled in a Z direction through the 3D geological model data.

Cross-section A vertical slice defined by a start and end point through the 3D geological model data

Horizontal Slice A horizontal slice given at a Z depth level through the 3D geological model data

Synthetic Cross-sections, boreholes or horizontal slices which are constructed using data from the triangulated surfaces stored in the Subsurface Viewer.

Topomap A map showing topographical features and landmarks of the Earth's surface.

Appendix 2

Guide to Subsurface Viewer Model Property Attribution

Properties are bulk attributed to superficial lithostratigraphical units based on typical values recorded in boreholes. Below is a list of properties encountered in the Subsurface Viewer with explanations of codes.

NAME

| | |
|---------------------|--|
| Mgr | Made and Worked Ground |
| P | Peat |
| Law | Law Sand and Gravel Member |
| Guf | Gourock Sand Member |
| Karn | Killearn Sand and Gravel Member |
| Pais | Paisley Clay Member |
| Bron | Bridgeton Sand Member |
| Ross_sand | Ross Sand Member |
| Ross_sz | Ross sand Member (silty-sand) |
| Bhse | Broomhouse Sand and Gravel Member |
| Bhse_clay | Broomhouse Sand and Gravel Member (clay) |
| Bhse_sand1 | Broomhouse Sand and Gravel Member (sand) |
| Bill | Bellshill Clay Member |
| Witi | Wilderness Till Formation |
| Base_UCMS_lense_top | Base Upper Coal Measures |
| Base_GU_lense_top | Base Glasgow Upper Coal |
| Base_GE_lense_top | Base Glasgow Ell Coal |
| Base_KILC_lense_top | Base Kiltongue Coal |
| Base_ULGS_lense_top | Base Upper Limestone Group |
| Base_KDG_lense_top | Base Knightswood Gas Coal |
| fDechmont_lense_top | Fault (various as named) |

LITHOSTRAT_CODE

As in table above

COMPOSITION

| | |
|------------------|---|
| NULL | No entry |
| SZ | Silty-Sand |
| C | Clay |
| SV | Sand and Gravel |
| CZ | Silty-Clay |
| CZSVLB | Mixture of clay, silt, sand, gravel, cobbles and boulders |
| VBS | Gravel, boulders and sand |
| Sedimentary Rock | Sedimentary Rock |
| Fault | Fault |

GENDER

| | |
|------|------------------|
| Lit | Littoral |
| Mar | Marine |
| Glac | Glacial |
| Flv | Fluvial |
| Lac | Lacustrine |
| Glal | Glaciolacustrine |
| Gflv | Glaciofluvial |
| NULL | No entry |

ORIGIN

Self explanatory

GEOLOGICAL_UNIT

Self explanatory

AGE

Self explanatory

AQUIFER_FLOW_TYPE

Self explanatory

AQUIFER_PRODUCTIVITY

| | |
|-------------|-----------------|
| High | High yields |
| Moderate | Moderate yields |
| Non Aquifer | No water stored |

1. PERMEABILITY

Self explanatory

2. ENGINEERING_DESCRIPTION

| | |
|------|--|
| Eng1 | Highly variable, very soft to stiff CLAY, loose to very dense with very weak SAND and or GRAVEL to strong rock to cobble, or boulder size, mix of natural and man made material: MGR (Made Ground undifferentiated) |
| Eng2 | Very soft to firm CLAY, loose to medium dense silty SAND and SAND, sometimes organic or with peat: LAW (Law), GUF (Gourock) |
| Eng3 | Firm to very stiff / dense to very dense gravelly sandy CLAY or SAND and GRAVEL with cobbles and boulders: WITI (Wilderness) and BNTI (Baillieston Till). |
| Eng4 | Very soft to firm, uncompact to compact (loose) laminated SILT and CLAY and some sand beds. LAC (Lacustrine), KEL (Strathkelvin Formation), PAIS (Paisley). |

| | |
|------|--|
| Eng5 | Firm to stiff laminated SILT and CLAY: BRLL (Broomhill Clay) and BHSEC (fine grained), CLAY |
| Eng6 | Loose to medium density silt SAND and SAND occasional gravel: BRON (Bridgeton), ROSS (Ross) and KARN (Killearn) |
| Eng7 | Medium to very dense silty or clayey, gravelly SAND and/or GRAVEL sometimes or occasional cobbles and boulders. BHSE (Broomhouse), BHSES (Broomhouse-sand), SAGR (Glacifluvial sand and gravel), CADR (Cadder Sand). |
| Eng8 | Highly compressible PEAT. |
| NULL | No entry |

3. RUNNING_SAND_AND_SILT

| | |
|------|---|
| Run1 | Moderate hazard, may run if saturated. |
| Run2 | Low hazard; unlikely to run but some parts may flow if saturated and in some circumstances. |
| Run3 | No hazard, unlikely to run. |
| NULL | No entry |

4. PLASTICITY

| | |
|-------|---|
| Plas1 | Medium to high liquid limit. |
| Plas2 | Low to medium liquid limit. |
| Plas3 | Sometimes or occasionally intermediate to high liquid limit |
| Plas4 | Sometimes or occasionally low to intermediate liquid limit |
| Plas5 | Very high to extremely high liquid limit. |
| Plas6 | Plasticity unknown |
| Plas7 | Not plastic. |
| NULL | No entry |

5. GEOTECH

| | |
|---------|---------------------|
| PEAT | Peat |
| LOOSE | Loose |
| DENSEV | Very dense |
| SFTFRM | Soft to firm |
| DENSEM | Medium Dense |
| UNKNOWN | Unknown |
| VAR | Variable |
| FIRM | Firm |
| STIFF | Stiff |
| DENDENV | Dense to very dense |
| NULL | No entry |

Appendix 3

CONTENTS OF ENCLOSED CD

Geological ARC Surfaces

- Bedrock
 - ASCII Grids (asc)
 - Faults (adf)
 - Shapes and Point Data (shp)
 - Surfaces (adf)
- Superficial
 - 10m grid size bases (tif)

Report

- Report

Subsurface Viewer Models

- Model.exe with uncertainty rasters
- Model.exe without uncertainty rasters
- Guide to model property attribution
- Subsurface viewer user manual

Uncertainty Rasters

- Bedrock
- Superficial

Groundwater ARC Surfaces

- Recharge Model
- Flow Model