3D geological models and their hydrogeological applications: supporting urban development – a case study in Glasgow-Clyde, UK

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ABSTRACT:

Urban planners and developers in some parts of the United Kingdom can now access geodata in an easy-to-retrieve and understandable format. 3D attributed geological models and associated GIS outputs developed by the British Geological Survey (BGS) provide a predictive tool for planning site investigations for some of the UK's largest regeneration projects in the Thames and Clyde River catchments.

Using the 3D models, planners can get a 3D preview of properties of the subsurface using virtual cross-section and borehole tools in visualization software, allowing critical decisions to be made before any expensive site investigation takes place, and potentially saving time and money. 3D models can integrate artificial and superficial deposits and bedrock geology; and can be used for recognition of major resources (such as water, thermal and sand and gravel), for example in buried valleys; groundwater modelling; and assessing impacts of underground mining. A preliminary groundwater recharge and flow model for a pilot area in Glasgow has been developed using the 3D geological models as a framework.

This paper focuses on the River Clyde and the Glasgow conurbation, and the BGS's Clyde Urban Super-Project (CUSP) in particular, which supports major regeneration projects in and around the City of Glasgow in the west of Scotland.

Figure legends:

Figure 1 – Location of the Clyde catchment and Glasgow conurbation with some of the available multidisciplinary datasets. OS topography © Crown Copyright. All rights reserved. 100017897/2009.

Figure 2 – Clyde Gateway Pilot 3D superficial deposits model, looking southeast (area 10km x 10km, vertical exaggeration x5) Clyde Gateway Pilot 3D superficial deposits model, looking southeast (area 10km x 10km, vertical exaggeration x5): dark brown –

anthropogenic deposits; red – sand and gravel ; light yellowish brown – sand; green - clay; orange – sand; pink – sand and gravel; blue – till

Figure 3 – Superficial deposits thickness map of the Midland Valley of Scotland (white where superficial Superficial deposits thickness map of the Midland Valley of Scotland (white where superficial deposits <1m thick; grey where >1m and <5m thick; green 5-<20m thick; orange 20-<70m thick; red≥70 m thick) with network of detailed urban 3D models in the Glasgow area (red squares, each 5km by 5km in size) and GSI3D regional cross-sections along the ‘Kelvin’ buried valley (irregular red lines).

Figure 4 – GSI3D model looking northeast along the ‘Kelvin’ buried valley (light blue- Baillieston Till Formation lining the base of the buried valley; pink – Cadder Formation (mainly sand and gravel infilling the buried valley); blue at surface and overlying the Cadder Formation – Wilderness Till Formation; buff - alluvial deposits (along the Kelvin valley etc.)

Figure 5 – Clyde Gateway Pilot 3D Bedrock model, looking west (vertical exaggeration x3); KDG (white) – Knightswood Gas Coal; ULGS – Index Limeston, Upper LimestoneFormation (blue); KILC – Kiltongue Coal (purple); GE – Glasgow Ell Coal (yellow); GU – Glasgow Upper Coal (green); UCMS – base of Scottish Upper Coal Measures Formation (pink).

Figure 6 - Areas (bluish grey) in which mining has been identified within 30 m of rockhead (bedrock interface) within and adjacent to the City of Glasgow (grid in 10 km intervals)

Figure 7 – Clyde Gateway Pilot 3D Geological Model; combined model uncertainty for Kiltongue Coal seam (KILC) draped on the geological surface in GOCAD™. The uncertainty colour scheme is relative and increasing uncertainty is reflected by the change from purple to blue, green, yellow, orange and red**.**

Figure 8 – Clyde Gateway Pilot 3D Geological Mode; data density uncertainty for the Wilderness Till Formation (WITI); area as in Figure 2.

Figure 9 **–** Clyde Basin calculated distributed long term average recharge from ZOODRM

Figure 10 – ZOOMQ3D (Run 1, Merritt et al. 2009) simulated groundwater head contours (m AOD_for Clyde Gateway and adjacent plotted area with observed groundwater level point measurements (m AOD)

KEY WORDS: Glasgow, Clyde, regeneration. 3D models, uncertainty, GIS, groundwater, leaching, engineering.

INTRODUCTION

Environmental science communities are increasingly encouraged by governments and funding agencies to work closely together to develop process models, especially time series models, to improve understanding of the environment. Key drivers are global climate change and its impacts, including extreme weather events and the need to reduce CO_2 emissions, and an increasing focus on sustainable development. Process models are required to enable predictions to be made to support decision making, from which fit-for-purpose policy can be developed.

The British Geological Survey (BGS) is helping to meet this need by building on its spatial 3-dimensional (3D) modelling capability, to undertake four cross-cutting projects, one of which (Data and Applications for Environmental Modelling (DAEM)) will drive forward the development of a UK-wide ‘Environmental Impacts Modelling Platform’ (EIMP). The cross-cutting projects are an important component of the BGS Strategy for 2009-14 (British Geological Survey 2009) and are fostering not only a culture of multidisciplinary integration between teams of geoscientists within BGS, but are also cultivating external collaboration with partners from widely differing backgrounds, i.e. transdisciplinary linkages with socio-economists, environmentalists and health experts. Such partnerships develop most effectively where there is a willingness to share data and knowledge openly.

The close cooperation and feedback from end-users of the models and other outputs is also essential to the success of the cross-cutting projects.

This paper concentrates on one of these cross-cutting projects, the Clyde-Urban Super-Project (CUSP), which is focussed on the Glasgow conurbation and the Clyde Basin, within the Midland Valley of Scotland. This region is the focus of Scotland's largest post-industrial regeneration activity. However, many of the issues discussed are generic and apply equally well to BGS's other cross-cutting projects (DAEM, the Thames Basin Project and the Permo-Triassic Aquifers Project).

URBAN DEVELOPMENT AND THE CLYDE-URBAN SUPER-PROJECT (CUSP)

The River Clyde is one of the more strategically important rivers in the United Kingdom, and the third longest in Scotland. It flows through the heart of the Glasgow conurbation (Figure 1), Scotland's most densely populated area, with a population of approximately 1.2 million. During the 19th and earlier parts of the 20th centuries, the river was important for shipbuilding and trade and was key to Glasgow's rapid expansion, when the city lay claim to be the third largest in Europe, after London and Paris. Other heavy industries also developed in the lower catchment of the River Clyde, and there was extensive mining for coal and ironstone, which resulted in large parts of the City of Glasgow being undermined, often at shallow levels. The mining and heavy industry declined and ceased during the second half of the 20th century, and now only limited heavy industry remains. As a consequence, Glasgow has a largely post-industrial landscape with significant areas of dereliction and associated social deprivation, problems which are being addressed by local authorities and the Scottish Government.

The Clyde Corridor is the national regeneration priority for Scotland over the next 25 years. This is a zone bordering the River Clyde which encompasses the Clyde Gateway (Figure 1) and Clyde Waterfront urban development initiatives. Such long-term regeneration is intended to stimulate economic growth on a national scale, drive smaller community regeneration projects, and tackle the concentrated deprivation (Scottish Executive, 2006) which has stemmed from industrial decline.

[FIGURE 1 HERE]

The Scottish Government has emphasised that successful regeneration requires the public and private sectors to work together at all levels, and with the communities themselves, to create real economic and social change, with local (governmental) authorities being the key strategic player on the ground (Scottish Executive 2006). These aims and aspirations fit closely to BGS's own strategy (British Geological Survey 2009), which emphasises the need for effective partnerships with its stakeholders (government, their agencies, universities, commerce and the public) so that it can continue to acquire, collate and provide comprehensive and authoritative geoscience data and knowledge as the basis for the research and modelling that it, and others, carry out.

BGS is developing integrated and attributed dynamic shallow earth 3D models and comprehensive geoscientific databases of the Glasgow conurbation and the surrounding catchment of the River Clyde. BGS is achieving this with local authority partners, especially Glasgow City Council, with which it has developed a long-standing and fruitful partnership over many years, through the cross-cutting Clyde Urban Super-Project (CUSP), and parallel development of the Clyde Gateway 3D pilot geological model. The former covers the whole of the Clyde catchment and inner estuary. The latter covers key sites, including the Clyde Gateway regeneration and redevelopment area, major new road and motorway extension projects, and the infrastructure for a major sporting event, the Commonwealth Games, to be hosted by the City of Glasgow in 2014.

The 3D, and potentially 4D, models and datasets being developed will provide planners, developers and regulators in the Glasgow area with up-to-date, accessible environmental and engineering geoscience data and knowledge for regeneration and other urban development projects. Increasingly, in urban areas such as the Glasgow conurbation, these models are being used to solve complex geoscience problems and to improve the understanding of environmental processes within the 'Zone of Human Influence'. These include, for example, contaminant migration through soils, surface water and groundwater interaction, and mining hazards. Broader applications include the assessment of impacts of urban land use on ecosystem services; and environmental change at local to regional scales. There is also a growing emphasis on the evaluation and communication of uncertainty in data and 3D model output. The framework models are also being used as the platform for further modelling activities such as numerical groundwater modelling.

3D MODELS OF GLASGOW'S SUPERFICIAL DEPOSITS AND BEDROCK

BGS produces 3D models at a variety of resolutions, from national to regional and local; these equate respectively to scales of approximately 1:250,000, 1:50,000 and 1:10,000. The models focus on lithology, stratigraphy and structure, and are attributed with physical (e.g. engineering) and chemical properties. Local to regional scale (1:10,000 to 1:50,000) detailed models, which focus on characterising the near-surface superficial (including anthropogenic) deposits and shallow bedrock (less than 200 m depth), are generally considered to be of most use in urban planning and development (Kessler et al. 2005). The 3D models developed for the Glasgow conurbation and peri-urban surrounds are being produced at a scale equivalent to c.1:10,000 scale; those for the more rural parts of the catchment of the River Clyde are at a scale of c.1:50,000. The models digitally synthesise available, mainly subsurface, geoscience data from boreholes, geological maps, mine plans (related to the extensive 19th and 20th century coal and ironstone mining) and terrain models. Much of the data are already held in BGS's archives, but substantial bodies of data have also been provided by local authorities.

Two main models have been produced for the Glasgow area:

(i) The Clyde Gateway Pilot 3D Model is a bespoke model developed in partnership with Clyde Gateway Developments Ltd, Glasgow City Council, South Lanarkshire Council and Scottish Enterprise to assist regeneration and major development projects in the eastern part of the Glasgow conurbation. This covers an area of c.75 km^2, is based on an assessment of nearly 8000 coded boreholes, and incorporates c.250 line kilometres of interpreted geological cross-sections.

(ii) The Glasgow Conurbation model, which covers an area of c.625 km^2, and which is based on approximately 40,000 coded boreholes. This is based on 25 stand-alone models of the superficial deposits, and 5 separate bedrock models.

The GSI3D (©Insight GmbH) code has been used to build the models of the superficial deposits and artificial ground in the Glasgow area. GSI3D utilises a digital terrain model, geological surface outcrops and down-hole coded borehole data to enable the geologist to interpolate between boreholes and outcrops, or subcrops, to construct intersecting cross-sections (fence diagrams). The cross-sections and geological envelopes (limits of the geological surfaces) are used to build a surface in the GSI3D model (calculated by triangulation). More than 40,000 boreholes have been coded for modelling purposes within the Glasgow area alone. Models can additionally be attributed with geotechnical data (e.g. from the National Geotechnical Properties Database), hydrogeological data, and other properties; and published in the Subsurface/Lithoframe Viewer. This is an easy-to-use, intuitive, and interactive model-viewing tool which can create:

(i) models displaying the geology or other pre-selected applied themes (e.g. hydrogeological properties),

(ii) Geological maps (at surface and uncovered),

(iii) User defined synthetic borehole logs,

(iv) User-defined synthetic horizontal and vertical sections,

(v) Visualisation of the geometry of single and combined units, and

(vi) Model and map exports to ArcGIS© (geological surfaces as grids (*.asc); all points on a surface as x,y,z (*.asc); geological surfaces as GoCAD™ TINS (*.ts); map, 3D model, cross-section and borehole images as .jpg/.png formats), and hardcopy.

These outputs can be used in linear route assessment, in planning and refining development sites, and in planning site investigations. With the addition of new site investigation data and revision of the model, a revised ground model of the site can be created. The 3D geological model is, therefore, a powerful predictive tool and time saving asset that assimilates large amounts of urban geodata into one easy-to-use package. However, it must not be regarded as a substitute for detailed site investigation.

While bulk property attributions of these 3D geological models are useful for portraying general properties, such as engineering geological (Merritt et al. 2006) or hydrogeological (Kessler et al. 2005) characteristics of an area, they do not portray the inherent variability of each unit needed for more site-specific considerations. At present, insufficient data are available on the variability of all units for more detailed, cellular (voxel) attribution, although this is a longer term objective. Therefore, a range of GIS methods has been developed to present and interrogate the geodata (Entwisle et al. 2008).

Superficial Deposits

The superficial deposit sequences in the Clyde Basin as a whole are relatively complex. They reflect successive advance and retreat of ice sheets, several marine inundations during and since the last glaciation, the development of terraces, the deposition of estuarine sediments, and local lakes, some infilled partly by peat deposits. The superficial deposits are dominated by glacial till, often resting on bedrock and comprising a matrix of clay, sand and silt with pebbles, cobbles and boulders (Hall et al. 1998). The till, deposited during successive glaciations, may be heavily compacted.

[FIGURE 2 HERE]

This complex glacial and post glacial history is reflected in the 15 superficial deposit units that have been identified and modelled within the Clyde Gateway Pilot 3D geological model (Figure 2) (Merritt et al 2009), with more than 20 within the full Glasgow Conurbation model. Within the Clyde Gateway area, the Wilderness Till Formation commonly rests on bedrock and is the most widespread, and in most parts is the oldest of the superficial deposit units within the model. Deposition of the Wilderness Till Formation was related to the Dimlington Stadial (28,000 to 14,000 BP), during which, at its maximum approximately 18,000 years BP, ice reached a thickness of more than 1 km in central Scotland (Hall et al. 1998). Overlying the Wilderness Till are glaciofluvial and deltaic sands and gravels, and glaciolacustrine silts and clays. The Clyde Basin is considered to have been ice free by c.13,800 years BP. Following deglaciation, when relative sea levels were higher than today, extensive spreads of raised marine deposits – sands, gravels, clays and silts – were laid down along the low ground adjacent to the present River Clyde. As relative sea levels approached those of today, alluvium began to be deposited on the flood plain of the River Clyde and other rivers in the area. The other main post-glacial deposit is peat, which occurs largely over upland areas and is only present locally within the Clyde Gateway model area. Some of the other units are also only locally distributed and of very variable thickness. These include the Cadder Formation, which underlies the Wilderness Till in some places. However, the Cadder Formation is far more important within some parts of the wider Glasgow Conurbation model, as described below. The considerable lateral and vertical heterogeneity in the Clyde Gateway Pilot 3D Model, even on a very local scale, is mirrored in extreme local variations in the engineering properties of the materials at any one location. This highlights the potential value of the 3D model in optimising building and infrastructure layouts within regeneration areas. As a result, both costs and issues related to unforeseen ground conditions can be reduced (the latter being the most common cause of construction project delays and overspend). The models also provide the framework for time-derivative numerical modelling of groundwater conditions and processes (recharge, groundwater flow etc.).

[FIGURE 3 HERE]

Buried Valleys

A substantial buried valley (or tunnel valley) has been identified and modelled beneath the floodplain of the River Kelvin in the northern part of the Glasgow Conurbation Model. The buried valley extends from west-south-west to east-north-east across the Midland Valley of Scotland, from the Clyde Estuary in the west to the Forth Estuary in the east (Figure 3). The buried valley is underlain and overlain by glacial till (the Baillieston Till and Wilderness Till respectively), but is largely infilled with glacifluvial sand and gravel of the Cadder Formation (Figure 4). The age of the Cadder Formation is relatively poorly constrained, but a rhinoceros bone from within the formation has been dated to 27,550 ^{14}C (+1370, -1680) years BP (Rolfe 1966). The Cadder Formation may be more than 80 m thick locally, and the entire succession of superficial deposits sequence within the buried valley is locally more than 100 m thick. The orientation of this feature is oblique to the present Clyde Valley (south-west to north-east), and modelling confirms that the feature cross-cuts the present Clyde catchment. The 3D modelling has demonstrated that the Kelvin buried valley has a markedly undulose base and is incised into bedrock. This suggests a subglacial origin for the buried valley (cf. BurVal Working Group 2006), although its true origin, and that of other apparently related buried valleys within and adjacent to the Midland Valley, is uncertain. The infill of the buried valley is an important potential resource in terms of the sand and gravel aggregates that it contains, of the aquifer that these sediments may form, and of the ground source heat that the buried valley may contain.

[FIGURE 4 HERE]

Bedrock

The Carboniferous bedrock which underlies the Glasgow area comprises simply folded but complexly faulted strata. The strata comprise mainly cyclic sandstones and mudstones with limestones, coals, ironstones and seatrocks. The coal seams and other stratigraphic boundaries included in the bedrock model (six layers in total) were recognised and modelled from sub-surface data (boreholes and mine plans) of varying data densities. The surfaces and faults were modelled using GoCAD™ software (Figure 5), a commercial 3D modelling package used widely in the hydrocarbon industry. The surfaces were then exported to GSI3D and embedded in the Subsurface Viewer.

[FIGURE 5 HERE]

Shallow mineworkings represent a local hazard, and have been the cause of damage to buildings as a result of collapse of workings from time to time, and so are a constraint for development within Glasgow urban area. Both the Clyde Gateway and Glasgow Conurbation 3D models have improved knowledge of the distribution and depths of mineworkings in the area (Figure 6), which will be of value in project planning in regeneration and other urban development areas.

[FIGURE 6 HERE]

Geological Model Uncertainty

For the high resolution Clyde Gateway Pilot and Glasgow Conurbation 3D models to be applied correctly, the uncertainty in the models must be identified and, where possible, quantified. Lelliott et al. (2009) have described a method to quantify uncertainty associated with geological surfaces in a 3D model, and tested this in relation to a 3D model of shallow superficial deposits. Their method uses Kernel density smoothing and resampling of borehole locations, and expert–user interaction to estimate uncertainty in geological surfaces based on data quality, data density and geological complexity.

The uncertainty in each bedrock and superficial deposit layer in the Clyde Gateway model has been calculated using the recently developed BGS Confidence Calculator v1.2, as described by Lelliott et al. (2009). This combines measurements of data density and geological complexity from an input Microsoft Excel® data file and ASCII modelled horizon grid. The uncertainty layers within the model, as for example in the GOCAD model (Figure 7), have also been exported in ArcGIS© 9.2 raster grid format for GIS applications, and within the GSI3D subsurface viewer for visualization.

[FIGURE 7 HERE]

The data density factor for the model includes assessments of the distribution of borehole, mining and map data. An influence distance of 200 m and a scale of 0.5 -100 were used to calculate the data density uncertainty. A grid of 100 by 100 with 500 iterations was used to calculate the geological complexity uncertainty. Together with the geological complexity weighting, the model uncertainty is greatest where there are least data and where the surface dip changes rapidly. The output is a grid (raster) file ranked from relative low to relative high uncertainty.

The relative combined uncertainty scale is translated by the user into uncertainty categories, with the lowest number representing the lowest uncertainty and the highest number the highest uncertainty. In the Clyde Gateway model, 5 categories have been considered, which are represented in ArcGIS© on the uncertainty grid by colour coding.

[FIGURE 8 HERE]

Lowest uncertainty (highest confidence) areas (=1) are those that are well constrained by geological data and where the geology is relatively simple. In the superficial deposits model, taking the Wilderness Till Formation (WITI) layer as an example (Figure 8), the areas of lowest uncertainty in terms of geological interpretation are shown in blue. Similarly, within the bedrock model, the lowest level of uncertainty is estimated to be of the order of ± 10 m in both the horizontal and vertical planes (i.e. in XYZ).

Average uncertainty (average confidence) areas (= 3) are those constrained by some geological data and where the bedrock geology is moderately complex, i.e. faulted or folded (or for superficial deposits, of variable thickness). In these areas, the uncertainty (or error) in the bedrock model, for example, might be considered to be of the order of ± 30 m in XYZ (i.e. within the volume of the model).

Highest uncertainty (lowest confidence) areas (= 5) are areas not constrained by any geological data and where the geology is complex, i.e. faulted or folded in the case of bedrock. Within the superficial deposits model, those areas of highest uncertainty within the Wilderness Till surface (Figure 8) are red to orange. This equates in the bedrock model to an uncertainty (or error) of c.± 70 m in XYZ.

HYDROGEOLOGICAL APPLICATIONS OF THE 3D GEOLOGICAL MODELS

Increasingly, 3D geological models such as the Clyde Gateway and Glasgow Conurbation models are being used to help solve complex geoscience problems, and there is scope for much more. The 3D geological framework provided by these models is the ideal basis for detailed investigations of subsurface characteristics and processes, such as engineering geology, geohazards, and even archaeology. One particular area in which 3D geological modelling is potentially of great use is in investigating groundwater processes and increasing our understanding of groundwater systems, with wider implications for promoting sustainable urban drainage and for better understanding of contaminant transport through the soil and water environment, flooding, minewater hazards, sustainable ground source heat exploitation, and ecosystem services.

For example, a key concern within Glasgow is sustainable drainage, linked to flooding along tributaries of the River Clyde, with overloading of the largely combined (i.e. foul and storm water) sewer systems leading to increased pressure for onsite infiltration of storm water via sustainable drainage systems (SuDS). However, the long term impacts of widespread SuDS installation on groundwater and on groundwater-dependent surface water systems are unknown. To ensure real sustainability of urban drainage systems, a better understanding of the groundwater system is needed, which will depend on the availability of better data – e.g. from aquifer testing and groundwater level and quality monitoring – and on detailed modelling of groundwater, surface water and the interaction between them. The 3D geological models provide an excellent framework for numerical modelling of the shallow groundwater system and of surface water-groundwater interaction; and can help ensure effective groundwater monitoring by focusing attention on the most significant hydrogeological units.

In another example, the thermal potential of waters flowing through areas of former mineworkings beneath Glasgow is of growing interest to a number of stakeholders, and the 3D geological models can be used to help investigate the presence and thermal characteristic of these minewaters. Another potential thermal, as well as water supply, resource may be groundwater within the Kelvin buried valley, and assessment of this resource could be supported by the 3D geological model.

The application of the 3D geological models to these three issues in Glasgow – groundwater modelling, thermal potential, and groundwater monitoring – are discussed below.

GROUNDWATER MODELLING

Preliminary numerical groundwater modelling in the Glasgow area is concentrating on the hydrogeology of the superficial deposits aquifers in the Clyde Gateway area, but a preliminary recharge model for the whole of Glasgow has also been developed. The groundwater modelling has been done using the ZOOM family of numerical groundwater modelling codes, in particular the ZOODRM distributed recharge model (Mansour & Hughes 2004) and the ZOOMQ3D saturated groundwater flow model (Jackson & Spink 2004). Both these use a pre-processor called ZETUP and spatial input files from a GIS (Jackson & Spink 2004). ZOOM was developed using object-oriented techniques, a programming approach commonly applied in commercial software development but only relatively recently adopted in numerical modelling for scientific analysis. A purpose-written tool built in GSI3D is used to convert data from GSI3D to ZOOMQ3D.

This is the first numerical groundwater modelling at greater than site-specific scale that has been done in Glasgow, and will greatly enhance the understanding of the groundwater system. The model provides the first detailed estimates of recharge for the city, partitioned into the various recharge sources, and the first quantitatively based simulations of shallow groundwater flow paths beneath the city.

Groundwater recharge for the whole of the Glasgow urban area has been modelled using ZOODRM (Figure 9). Distributed rainfall, evaporation and land use were used to calculate recharge to un-sealed areas (e.g. gardens and parks) using the soil moisture deficit method (Penman 1948, Grindley 1967). The recharge model incorporates overland water routing to sewers and culverts and the dominant urban recharge source, which is leakage from sewers and pressurised water mains.

[FIGURE 9 HERE]

A conceptual model of the 3D groundwater system in the superficial deposits in the Clyde Gateway area has been developed based on the geological framework provided by the Clyde Gateway Pilot 3D geological model. The groundwater conceptual model is greatly simplified compared to the number of layers in the 3D geological model, in view of the comparatively limited availability of hydrogeological data for Glasgow, particularly on the hydraulic properties of the different geological units, and on groundwater levels, including interval (time-series) data. Recharge values calculated by ZOODRM are transferred as one of the inputs to the groundwater flow model. Other inputs include hydrogeological, geological and hydrological data including river/stream flows, groundwater levels, and soil, artificial ground, superficial deposits and bedrock properties including estimated permeability based on similar hydrogeological units elsewhere (no measured permeability values exist for the Glasgow area). The model then simulates groundwater levels in the superficial deposits aquifers.

[FIGURE 10 HERE]

To date, a preliminary, unvalidated steady state run has been done to predict groundwater levels in the superficial deposits (Figure 10). This should be viewed as illustrative of the type of groundwater system considered to exist in the Clyde Gateway area. Where measured groundwater level data are available, these have been used to constrain the model. However, groundwater level data for Glasgow are scarce, and often of poor quality. These issues are discussed in the section Groundwater Monitoring, below.

Modelled groundwater levels have been exported from ZOOMQ3D and displayed within GSI3D. Other outputs, including predicted groundwater discharges to surface waters, are displayed as appropriate in ArcGIS®.

The steady state model can be used to undertake predictions of the impact of particular scenarios, such as the possible discharge of stormwater to the ground from Sustainable Urban Drainage Schemes (SuDS), climatic variations, or groundwater abstraction.

THERMAL POTENTIAL

The thermal potential of waters flowing through areas of former mineworkings beneath Glasgow is of growing interest to a number of stakeholders. A small-scale scheme extracting heat from water abstracted from minewater is already in operation (Banks et al.

2003, Banks et al. 2009), and BGS has recently carried out an initial assessment of the thermal resources in minewaters beneath the Glasgow area (Ó Dochartaigh 2009). Further work is currently being done to quantify that resource, using the 3D geological models of the bedrock geology as a basis for understanding the overall groundwater system. The future incorporation of information on former mineworkings into the 3D geological models will further enhance the opportunities for investigating the thermal resource, in particular by enabling more detailed thermal modelling.

The 3D geological modelling of the Kelvin buried valley will also be a key component of future work to model the water supply and thermal resource potential within the valley.

GROUNDWATER LEVEL MONITORING

The lack of basic groundwater data is a major limitation on improving our understanding of the groundwater system in Glasgow – e.g. on the development of numerical groundwater models – and therefore to our effectiveness in addressing issues such as Sustainable Drainage Systems (SuDS), flooding and developing thermal potential. One of the key datasets is groundwater levels, needed to develop a conceptual understanding of where groundwater exists, how and where it flows, and how this varies through time. Generating more widespread, more frequent, more consistent, and carefully measured and constrained groundwater level data is fundamental to further research on issues such as groundwater-surface water interaction (including the role of groundwater in flooding). The 3D geological models provide the basic framework for interpreting groundwater level data in the context of the whole groundwater system, and can be used to focus groundwater monitoring efforts where they will be most effective.

There are a number of issues surrounding the measurement and interpretation of groundwater levels. Any available groundwater level data can be subject to various errors, both of measurement and interpretation. Lovatt (2008) has investigated the applicability of various approaches to using available groundwater level data for Glasgow, which are of variable quality. Groundwater level data were collated from existing records for a trial area around the Clyde Gateway in central-east Glasgow, and used to interpolate new groundwater level maps. However, the existing spatial distribution of high quality data is not sufficient to allow the interpolation of a groundwater level surface even across the trial area, let alone across the whole city. In Glasgow, groundwater levels appear to show significant variation both temporally and spatially. Visible temporal variations are tidal or seasonal (datasets are not long enough to infer any longer-term variations). They vary from less than 0.5 m to more than 6 m. Spatial variations can be significant: for example, boreholes less than 50 m apart have recorded average groundwater level depths that vary by more than 10 m. Much of the explanation for this spatial variability is likely to be the vertical and lateral complexity of the superficial deposits sequence in Glasgow, and additionally the impact of the underlying bedrock. The geological models provide the essential 3D context for understanding and characterising this variability.

Work is ongoing to develop a groundwater monitoring strategy for Glasgow, focusing intially on the central-east part of the city, and on groundwater levels in superficial deposits. Existing groundwater level monitoring data are being collated, in particular from Glasgow City Council, who are the recipients of data collected by contractors working on the main regeneration sites in this area, including the Clyde Gateway and Commonwealth Games sites. These monitoring data will be interpreted with reference to the 3D geological models to put the measured groundwater level data in the context of the hydrogeological units in this region and the overall groundwater system. Using this improved understanding of the shallow groundwater system, recommendations for future groundwater monitoring will be made, so that groundwater level data are collected at a suitable spatial and distribution and temporal frequency to reflect the geological and hydrogeological complexity beneath the city.

Future work will expand these efforts to investigate groundwater levels in the bedrock aquifers, again using the 3D geological models to interpret these in context and so develop a fuller understanding of the whole groundwater system.

CONCLUSIONS

Planners involved in some of the UK's, and Europe's, largest and most challenging regeneration projects can now access, via dedicated extranets, a wide range of geodata in an understandable and readily accessible format via the British Geological Survey's 3D attributed geological models and associated tools. The attributed 3D geological models, groundwater numerical models and other outputs for Glasgow and the Clyde Basin enable visualisation of the geological and hydrogeological systems. There is a wide range of ways of interrogating the geological models by generating and viewing synthetic (virtual) cross-sections and boreholes at any locations within the models, enabling users to have a predictive view of the geology and physical properties of the subsurface, and plots, and graphs which characterize modelled unit variability. These outputs can be used to communicate a broad range of geoscientific information to specialists and non-specialists alike. These products will also improve our understanding of complex geoscience issues such as the impacts of flooding and sea level change, hazards related to past mining, groundwater contamination, and the sustainable development of water, thermal and other resources. The integration of information from the 3D geological models with groundwater models and with GIS provides a powerful desk study tool to aid planning from the geoscience perspective, for example to optimise the layout of developments. The 3D geological and models have the potential to save time and money when planning site investigations for major construction projects: they can contribute to construction risk management and to potential reductions in project delays and project overspends by reducing risk especially in relation to unforeseen ground conditions.

Work is ongoing to combine digital geoscience data with environmental data from other disciplines, to provide fully integrated, up-to-date and accessible information and knowledge that will assist planners, developers and regulators in making holistic decisions about sustainable land-use, development and regeneration.

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REFERENCES

Banks, D., Skarphagen, H., Wiltshire, R. & Jessop, C. (2003): Mine water as a resource: space heating and cooling via use of heat pumps. Land Contam. Reclam., 11: (2) 191-198, London (EPP Publications).

Banks, D., Fraga Pumar, A. & Watson, I. (2009): The operational performance of Scottish minewater-based ground source heat pump systems. Q. J. Eng. Geol. Hydroge., 42: 347 – 357, London (The Geological Society).

Burval Working Group (2006): Groundwater resources in buried valleys – a challenge for geosciences: 303 S., Hannover (Leibnitz Institute for Applied Geosciences).

British Geological Survey (2009): British Geological Survey Strategy 2009-2014: Applied geoscience for our changing earth: 28 S., Nottingham (British Geological Survey).

Entwisle, D.C., Wildman, G, Reeves, H.J., Campbell, S.D.G., Merritt, J.E. & Monaghan, A.A. (2008): 3D modelling and geotechnical GIS for planning and development: an example from Glasgow, UK: In European eConference of the International Association for Engineering Geology: 6 S., 15-20 September 2008, Madrid, Spain (International Association for Engineering Geology).

Grindley, J. (1967): The estimation of soil moisture deficits: Meteorol. Mag., 96: 97-108 (Great Britain, Meteorological Office).

Hall, I.H.S., Browne, M.A.E. & Forsyth, I.H. (1998): Geology of the Glasgow District: Memoir for 1:50 000 Geological Sheet 30E (Scotland): 117 S, Nottingham (British Geological Survey).

Jackson, C.R. (2004): User's manual for the particle tracking model ZOOPT: British Geological Survey Internal Report: CR/04/141N, Nottingham (British Geological Survey).

Jackson, C.R. & Spink, A.E.F. (2004): User's manual for the groundwater flow model ZOOMQ3D: British Geological Survey Internal Report: CR/04/140N, Nottingham (British Geological Survey).

Kessler, H., Sobisch, H.G., Mathers, S., Lelliott, M., Price, S., Merritt, J.E., Ford, J., Royse, K. & Bridge, D. (2005): 3-D geoscience models and their delivery to customers. – In: Russell, H.A., Berg, R.G. & Thorleifson, L.H. (eds.): 3-D geological mapping for groundwater applications: Geological Survey of Canada Open File: 5048; 39-42 Ottawa, Canada (Geological Survey of Canada).

Lelliott, M.R., Cave, M.R & Wealthall, G.P. (2009): A structured approach to the measurement of uncertainty in 3D geological models. – Q. J. Eng. Geol. Hydroge., 42: 95-105, London (Geological Society of London).

Lovatt, M.J. (2008): Assessing the importance of depth to groundwater in a methodology for prioritising threats to groundwater quality from surface contaminants in the Clyde Gateway, Glasgow: unpublished MSc thesis, University of Strathclyde.

Mansour, M.M., & Hughes, A.G. (2004): User's manual for the recharge model ZOODRM: British Geological Survey Internal Report: CR/04/151N, Nottingham (British Geological Survey).

Merritt, J.E., Entwisle, D.C. & Monaghan, A.A. (2006): Integrated geoscience data, maps and 3D models for the City of Glasgow, U.K. – In: Culshaw M.G., Reeves, H., Spink, T. & Jefferson, H. (eds.) Engineering Geology for Tomorrow's Cities: Eng. Geol. Spec. Pub. 394: 114, London (Geological Society of London).

Merritt, J.E., Monaghan, A.A., Loughlin, S.C., Mansour, M., Ó Dochartaigh, B.E. & Hughes, A.G. (2009): Clyde Gateway pilot 3D geological and groundwater model: British Geological Survey Commissioned Report: 73 S., CR/09/005: Nottingham (British Geological Survey).

Ó Dochartaigh, B.E. (2009): A scoping study into shallow thermogeological resources beneath Glasgow and the surrounding area: British Geological Survey Internal Report: IR/09/024: Nottingham (British Geological Survey).

Penman, H.L. (1948): Natural evaporation from open water, bare soil and grass. – Proc. Roy. Soc., Lond.: Series A, 193: 120-145, London (The Royal Society).

Rolfe, W.D.I. (1966): Woolly rhinoceros from the Scottish Pleistocene. – Scot. J Geol., 2: 253-258, Edinburgh (Geological Societies of Edinburgh and Glasgow).

Scottish Executive (2006): People and Places, Regeneration policy statement summary, March 2006: 14, Edinburgh (Scottish Executive).

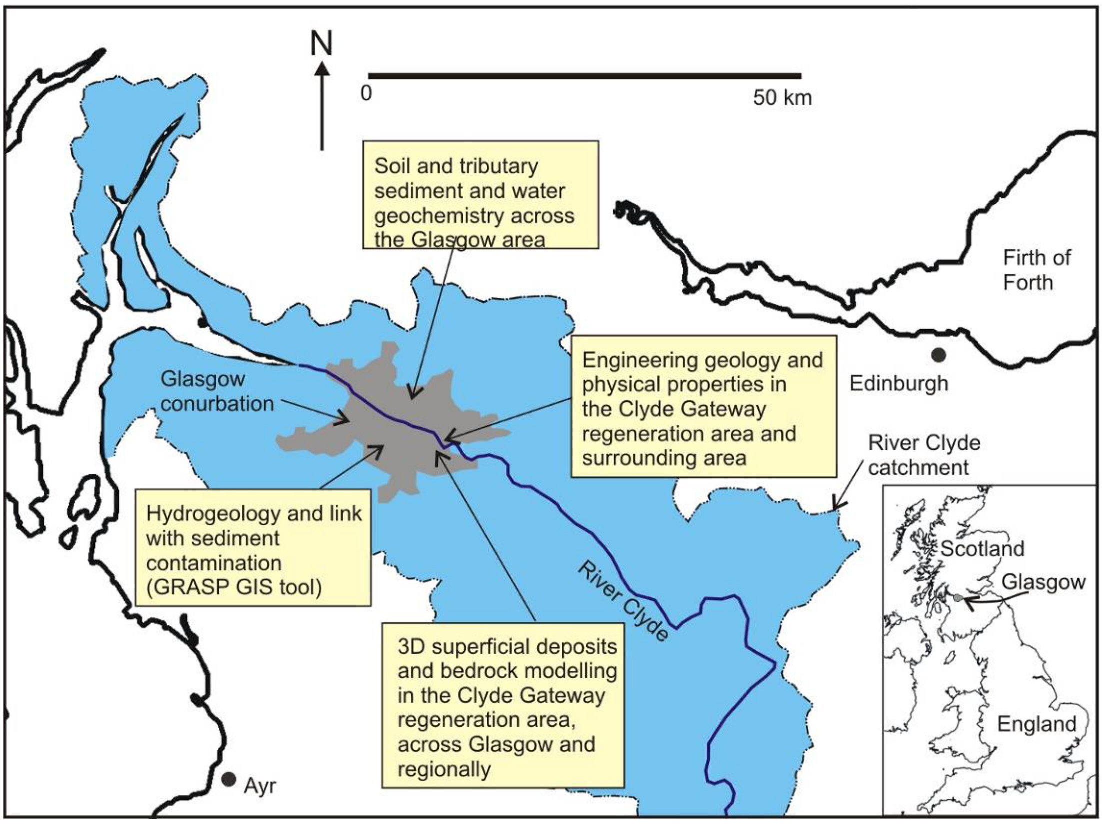

Figure 1 – Location of the Clyde catchment and Glasgow conurbation with some of the available multidisciplinary datasets. OS topography © Crown Copyright. All rights reserved. 100017897/2009.

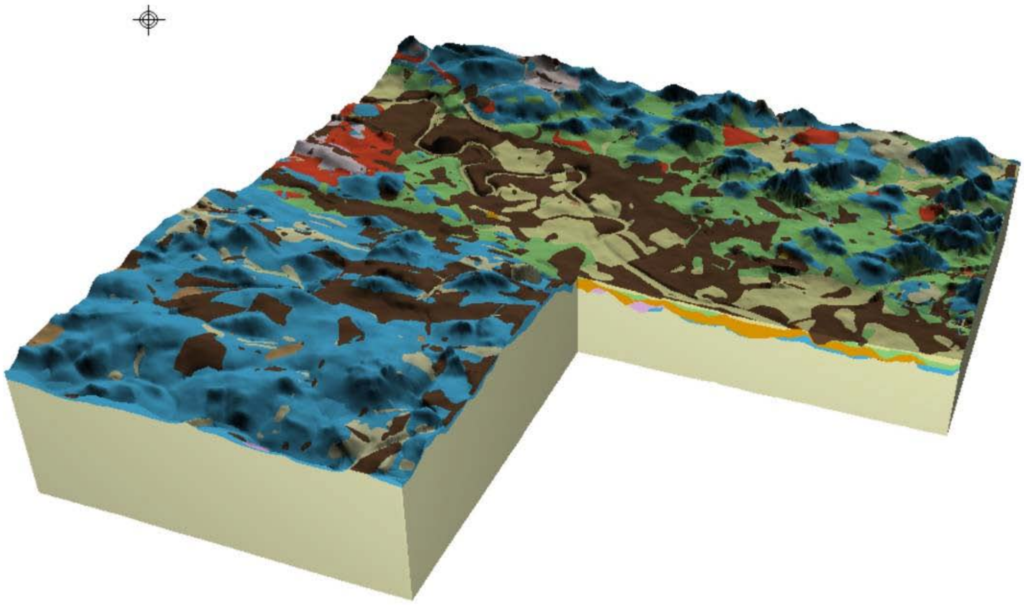

Figure 2 – Clyde Gateway Pilot 3D superficial deposits model, looking southeast (area 10km x 10km, vertical exaggeration x5): dark brown – anthropogenic deposits; red – sand and gravel ; light yellowish brown – sand; green - clay; orange – sand; pink – sand and gravel; blue – till

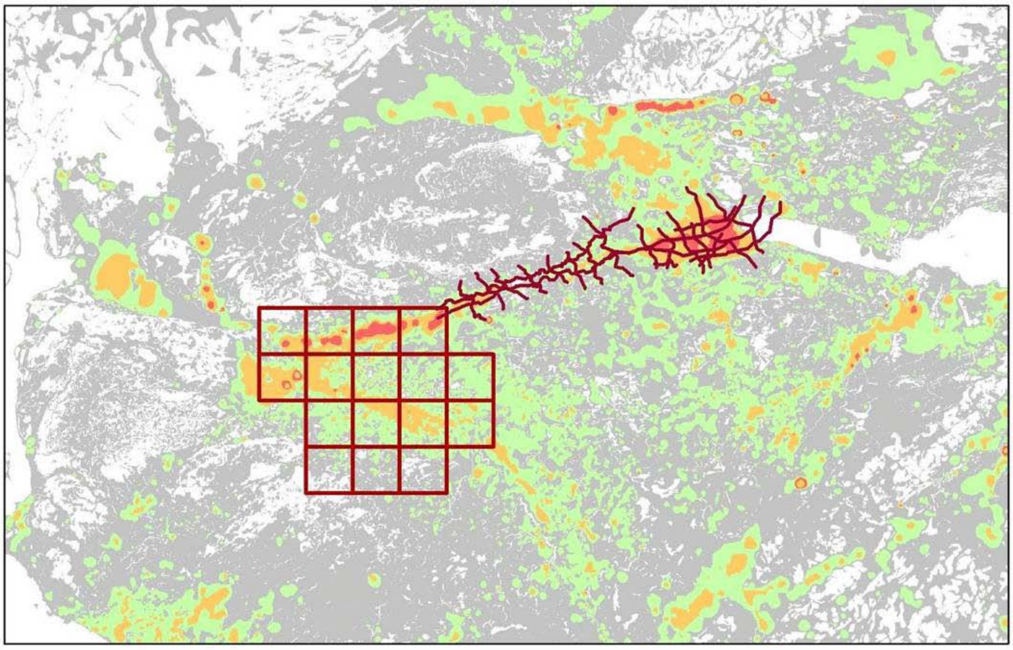

Figure 3 – Superficial deposits thickness map of the Midland Valley of Scotland (white where superficial deposits <1 m thick; grey where >1 m and <5 m thick; green 5 to <20 m thick; orange 20 to <70 m thick; red≥70 m thick) with network of detailed urban 3D models in the Glasgow area (red squares, each 5 km by 5 km in size) and GSI3D regional cross-sections along the 'Kelvin' buried valley (irregular red lines).

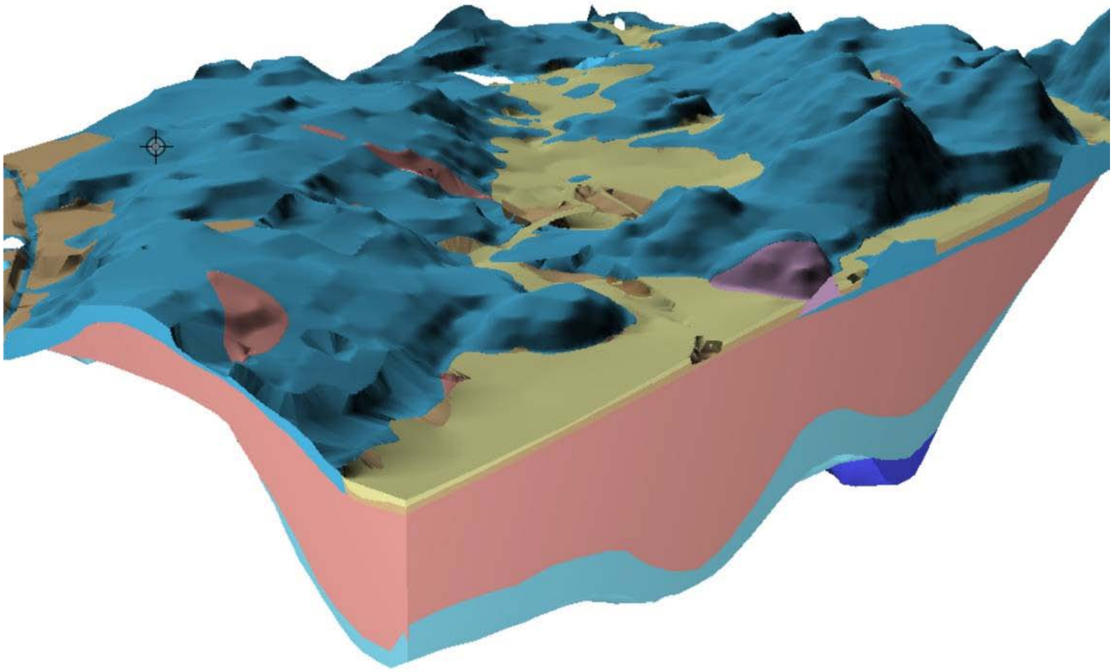

Figure 4 – GSI3D model looking northeast along the ‘Kelvin’ buried valley (light blue-Baillieston Till Formation lining the base of the buried valley; pink – Cadder Formation (mainly sand and gravel infilling the buried valley); blue at surface and overlying the Cadder Formation – Wilderness Till Formation; buff - alluvial deposits (along the Kelvin valley etc.).

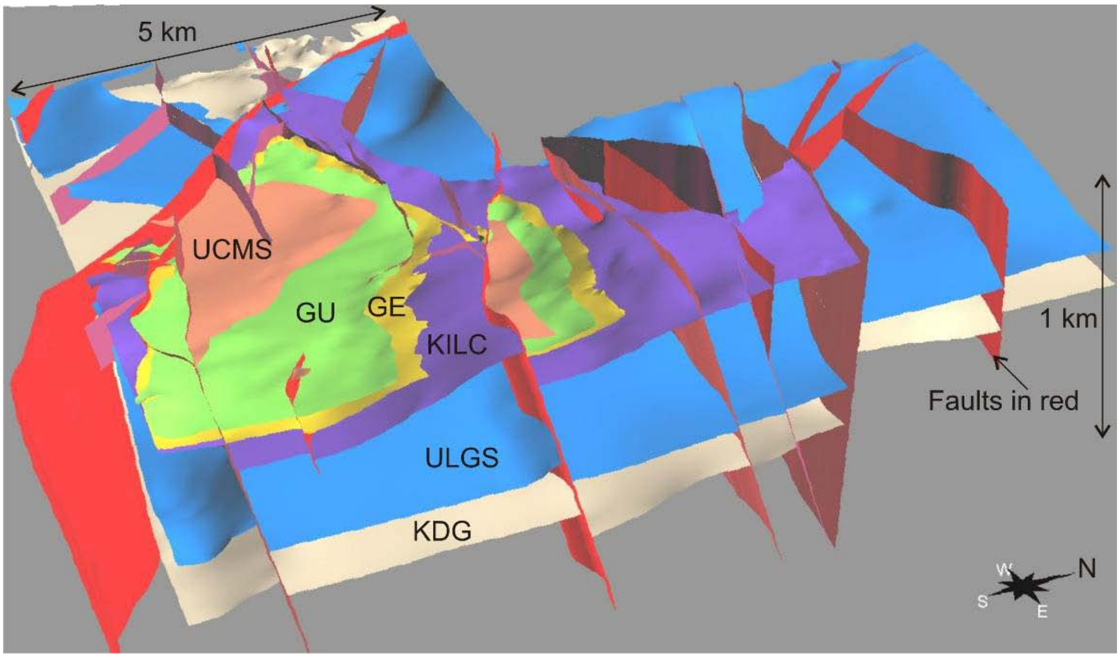

Figure 5 – Clyde Gateway Pilot 3D Bedrock model, looking west (vertical exaggeration x3); KDG (white) – Knightswood Gas Coal; ULGS – Index Limeston, Upper LimestoneFormation (blue); KILC – Kiltongue Coal (purple); GE – Glasgow Ell Coal (yellow); GU – Glasgow Upper Coal (green); UCMS – base of Scottish Upper Coal Measures Formation (pink).

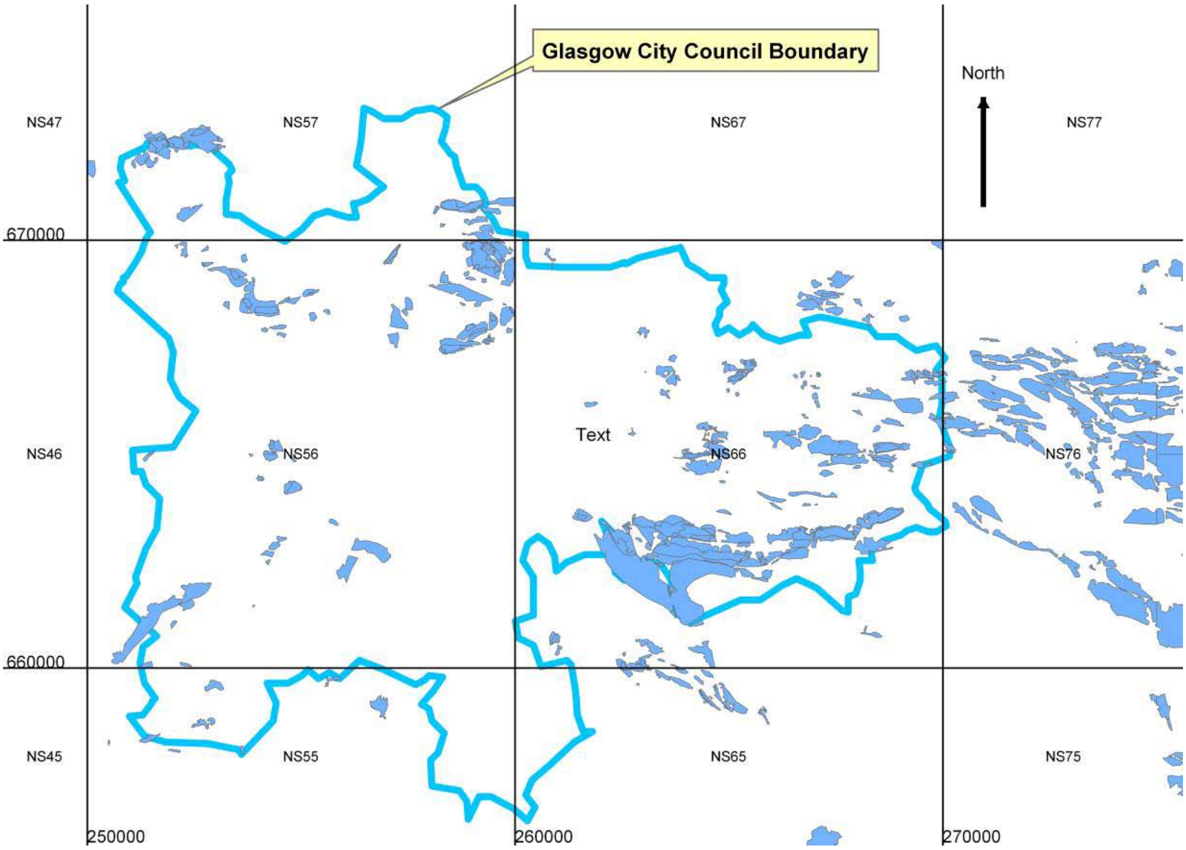

Figure 6 - Areas (bluish grey) in which mining has been identified within 30 m of rockhead (bedrock interface) within and adjacent to the City of Glasgow (grid in 10 km intervals)

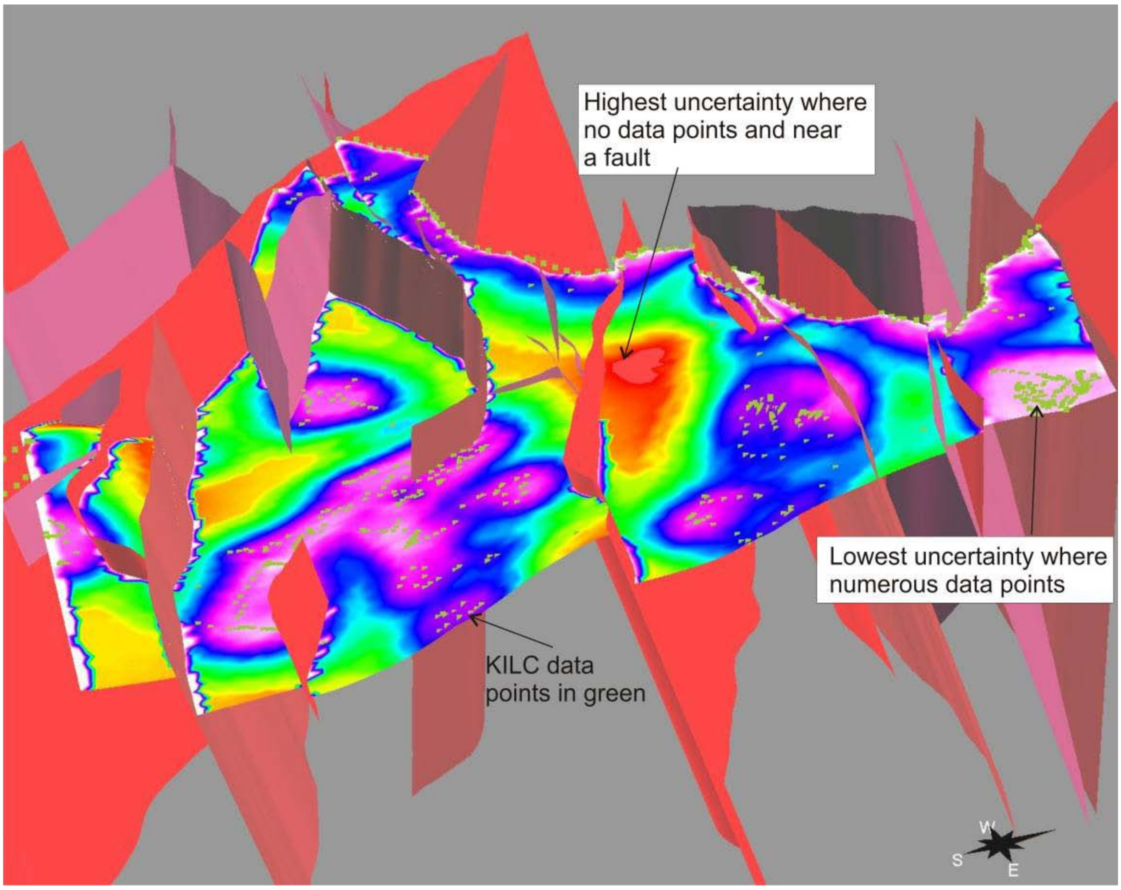

Figure 7 – Clyde Gateway Pilot 3D Geological Model; combined model uncertainty for Kiltongue Coal seam (KILC) draped on the geological surface in GOCAD™. The uncertainty colour scheme is relative and increasing uncertainty is reflected by the change from purple to blue, green, yellow, orange and red**.**

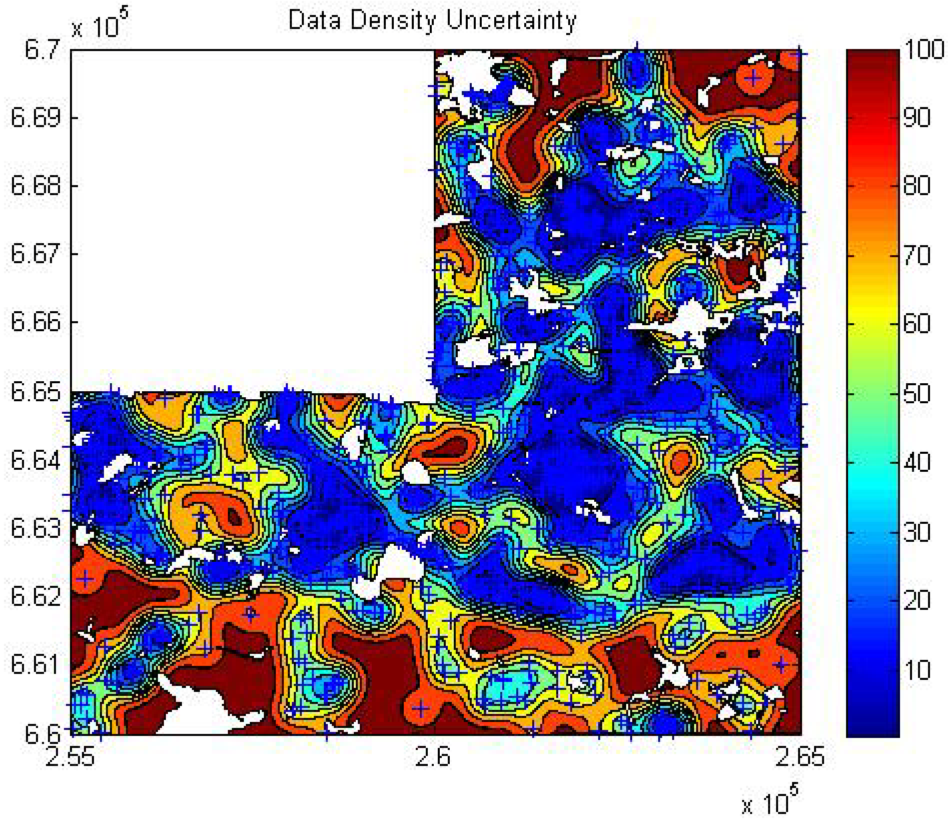

Figure 8 – Clyde Gateway Pilot 3D Geological Model; data density uncertainty for the Wilderness Till Formation (WITI); area as in Figure 2.

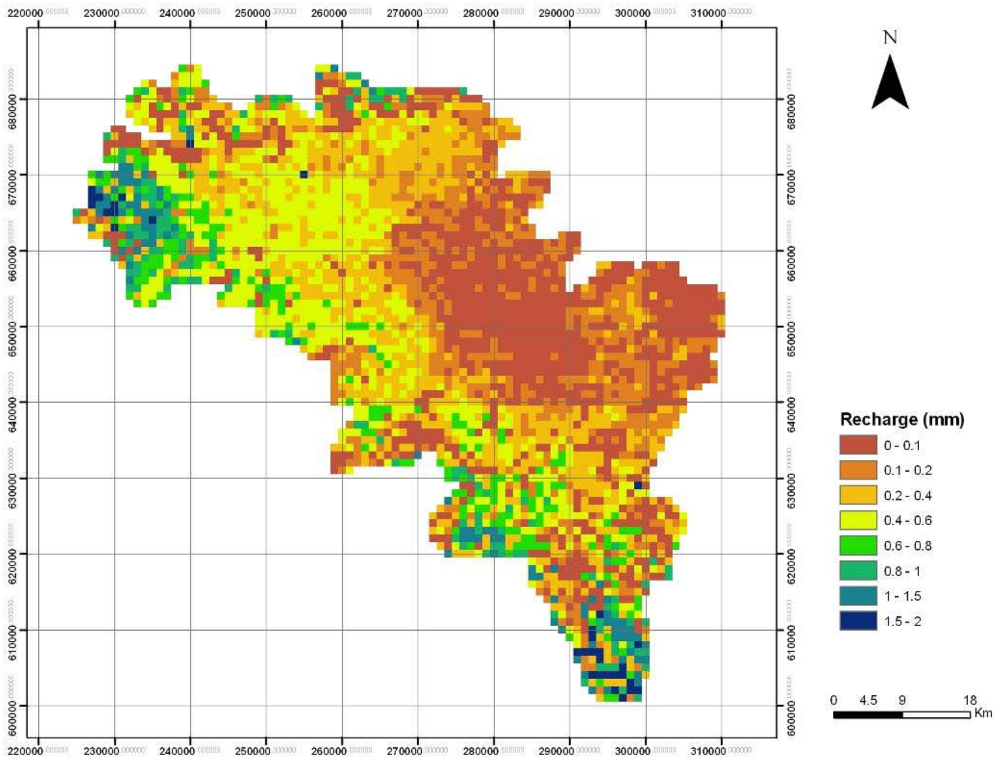

Figure 9 – Clyde Basin calculated distributed long term average recharge from ZOODRM

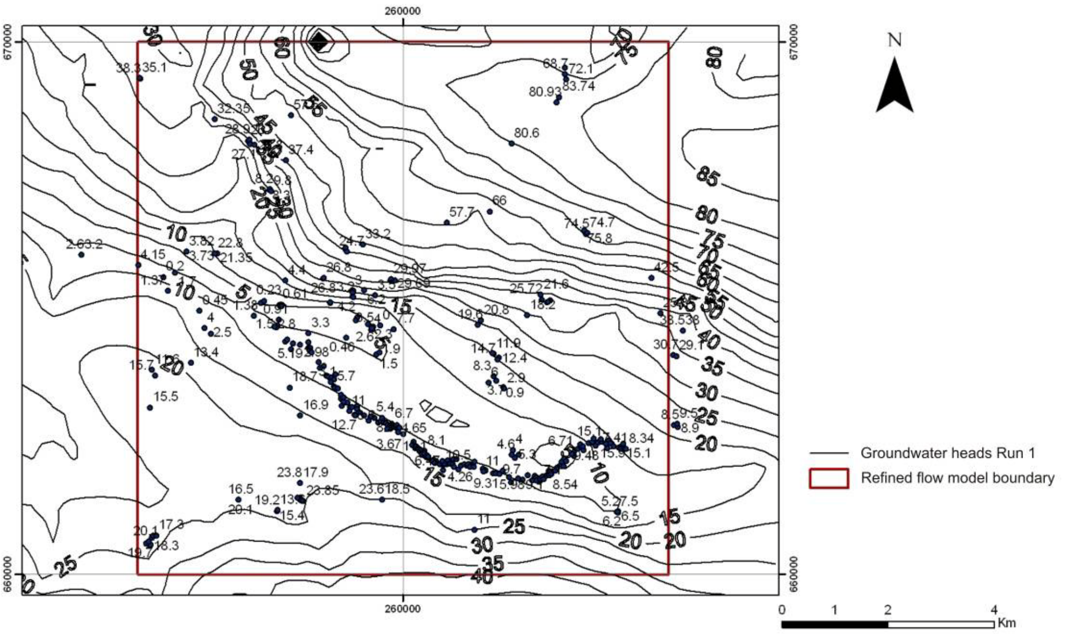

Figure 10 – ZOOMQ3D (Run 1, Merritt et al. 2009) simulated groundwater head contours (m AOD for Clyde Gateway and adjacent plotted area with observed groundwater level point measurements (m AOD)