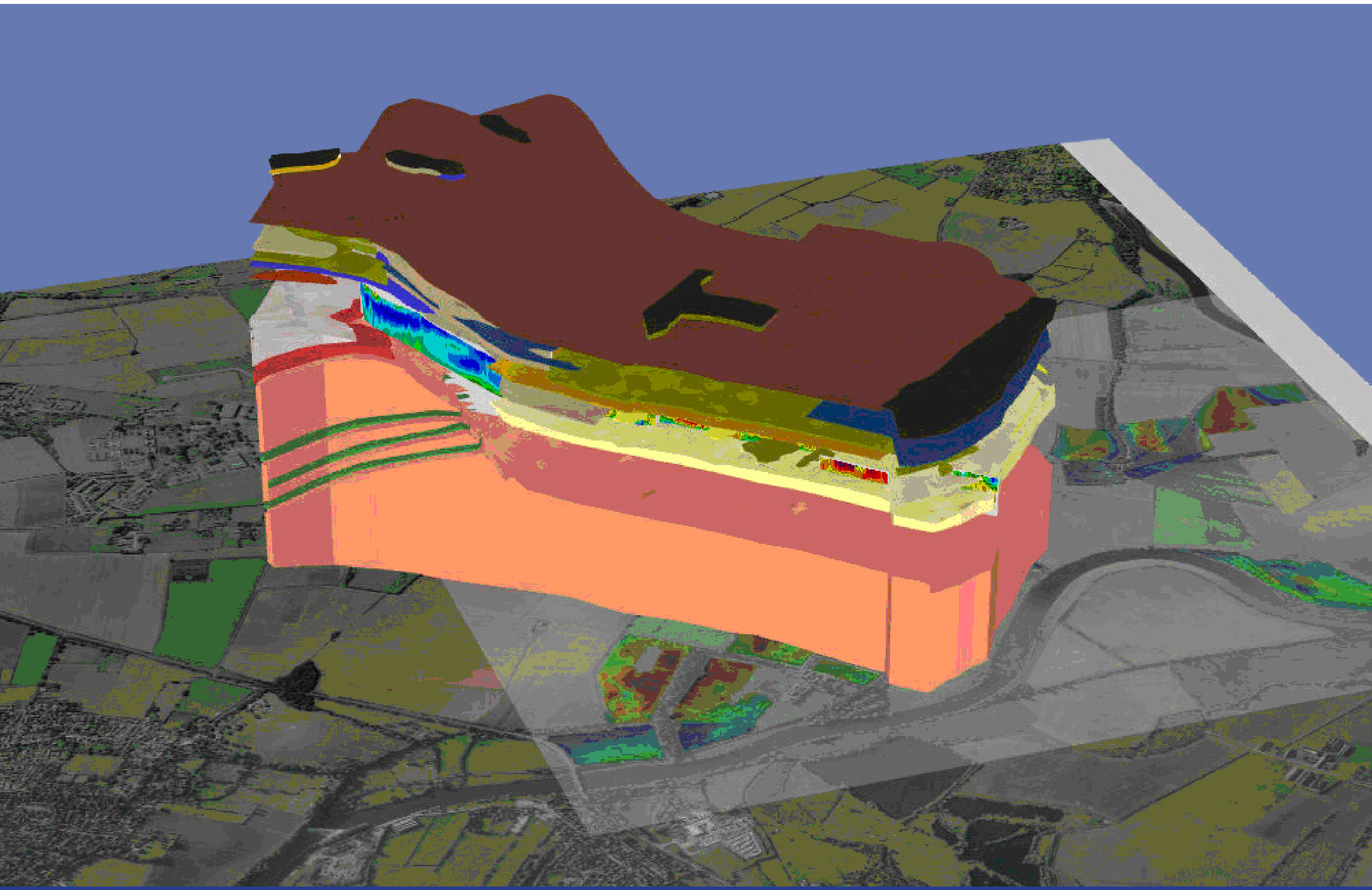
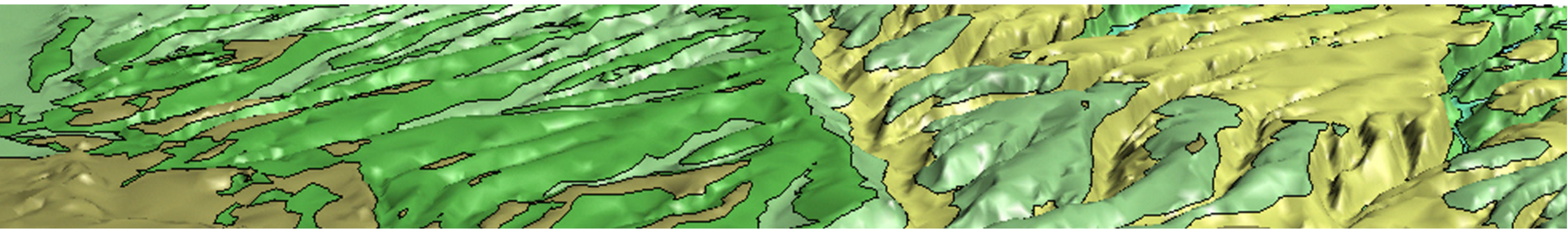


Extended Abstracts of the 2nd International GSI3D Conference

British Geological Survey, Keyworth, United Kingdom 2-3 September 2008

S J Mathers (editor)



BGS Open File Report OR/08/054

Extended Abstracts of the 2nd International GSI3D Conference

Editor: S J Mathers

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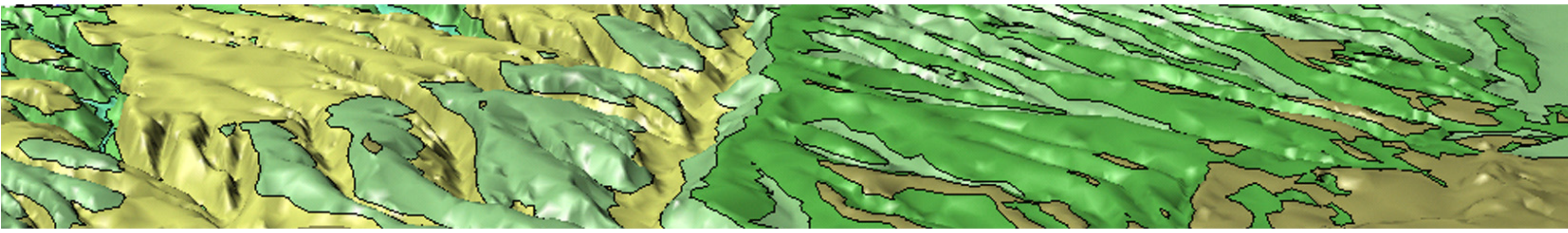
Design and production: Adrian Minks and Amanda Hill

Cover image:

3D model of artificial ground, soil horizons, superficial deposits and bedrock geology of the Shelford area of the Trent Valley, north-east of Nottingham displayed together with georeferenced air photos and geophysical sections and slices.

For more information on GSI3D see: http://en.wikipedia.org/wiki/GSI3D



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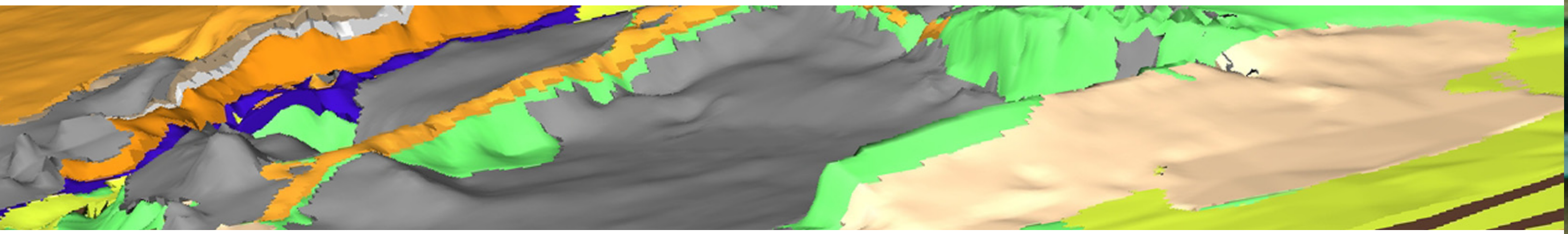

Foreword

Denis Peach, Chief Scientist, British Geological Survey

The challenges for the environmental research, regulatory and industrial communities presented by the possibility of rapid and extreme environmental change are substantial. Climate change, security of natural resources including energy, water and food, and the threat of environmental hazards, are all likely to impact significantly on our way of life, our environment and perhaps even our health. There has never been a greater need to understand the shallow Earth and its inherent processes that interact with humanity.

The construction of 3D geological models is greatly improving our knowledge base upon which we can build interdisciplinary research and better decision making to mitigate or adapt to environmental change and make secure our natural resources. The last ten years of evolution of geological modelling technology has ushered in a cultural change in thinking and understanding which should lead to a revolution in the numerical process modelling systems of the shallow Earth, whether they be for predicting stability in soils under changing climates, groundwater response to extreme rainfall or drought, or the capacity of deep saline aquifers to store carbon dioxide.

This volume and conference represents not an end to a development process but a beginning to better understanding and prediction of shallow earth processes and a major step on the way to the goal of living with environmental change.


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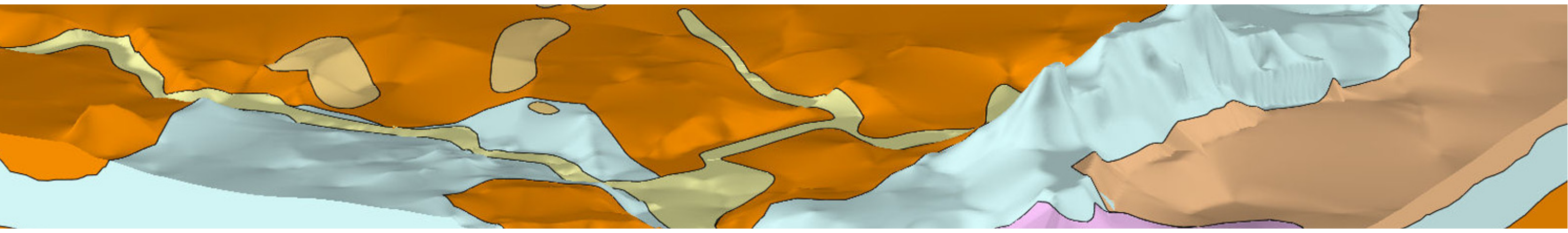
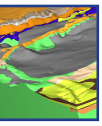
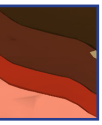


The past, present and future of GSI3D

Steve Mathers[1], Hans-Georg Sobisch[2], Ben Wood[1] and Holger Kessler[1]





The Geological Surveying and Investigation in three Dimensions (GSI3D) software tool and methodology has been developed over the last 15 years. The initial software was developed by Hans-Georg Sobisch as a tool for modelling shallow superficial-Quaternary sequences using a cross-section-based approach. From 2001–05 the British Geological Survey (BGS) became a test bed for the accelerated development of the tool and methodology, initially through the Digital Geoscience Spatial Model (DGSM) project. This project was tasked with examining available software solutions and recommending a way forward for BGS to realise the migration from a mapping to a modeling culture both in terms of working practices and outputs. Take-up of GSI3D in systematic surveying, urban, coastal and engineering studies soon followed. However, the implementation of GSI3D within BGS has only been possible because, by 2000, the Survey had: digital geological maps at scales effective for modelling; licensed, nationwide high-resolution Digital Terrain Model (DTM) coverage; and databases of both, borehole index and downhole data supported by corporate dictionaries for lithological and stratigraphical terminology. GSI3D now successfully utilises all this data, combined with the wealth of geological knowledge stored within the scientists' brains, to produce 3D geological models (Figure 1).

The BGS is now routinely building 3D models as part of its Science Budget programme, these are at four principal resolutions 1:1 million, 1:250 000, 1:50 000 and 1:10 000. These models are structured and attributed to meet the needs of a wide range of applied users, and ultimately, will take the place of the traditional geological maps. GSI3D is important in building shallow subsurface models at the more detailed scales in superficial and simple bedrock geology; Gocad is currently the other commonly used software at BGS and file exchange between the two packages is now possible meaning that some models are constructed by a combined approach. So far detailed GSI3D models have been constructed for Greater London and the Thames Gateway Development Zone, parts of southern East Anglia, Manchester and Merseyside, York and Glasgow.

GSI3D is now also frequently used in building 3D models as commercial contracts for clients such as the Environment Agency of England and Wales (EA), the UK water sector and local government. These are usually constructed to the clients' specifications and

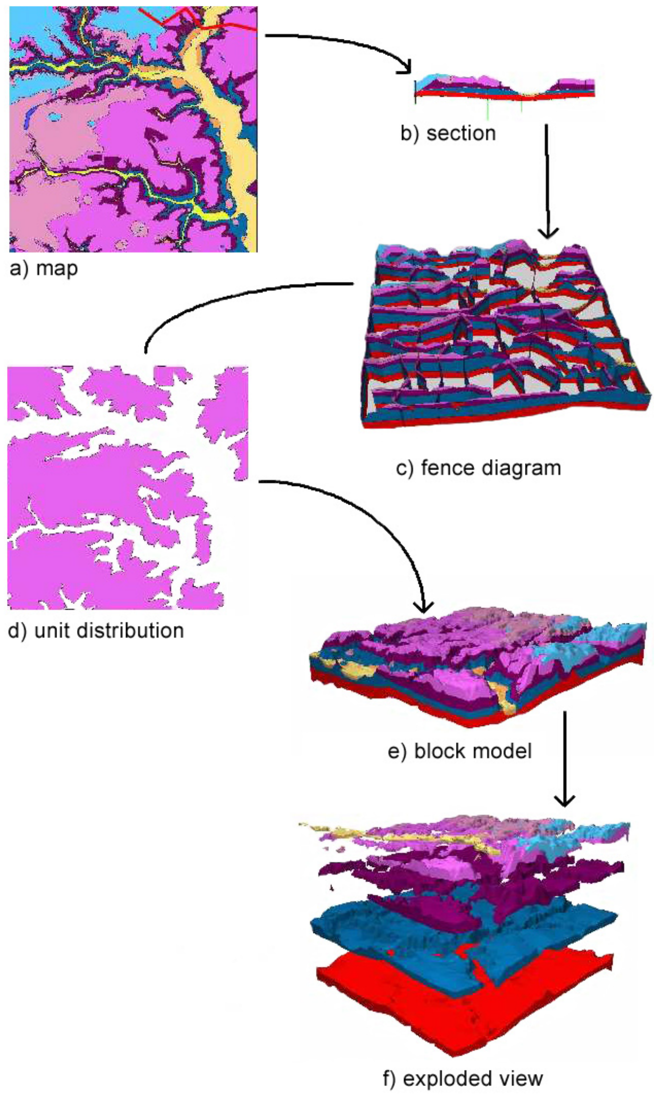
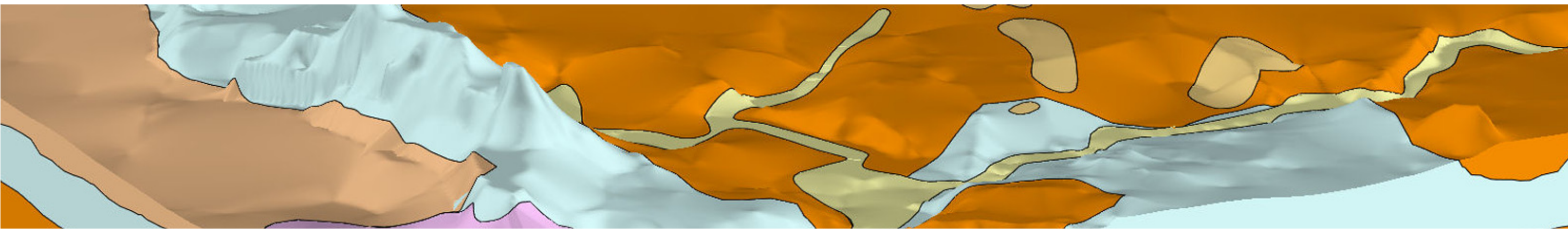


Figure 1 The GSI3D workflow for modeling superficial and simple bedrock geology. The example covers the TM24 map area around Woodbridge in Suffolk and extends down to the top surface of the Chalk. The Lambeth Group is in red overlain by the London Clay in blue, the Red Crag in maroon, superficial sands and gravels in shades of pink and Loestoft Till (boulder clay) in pale blue.

[1] British Geological Survey, UK, [2] INSIGHT GmbH Hochstadenstrasse 1-3, 50674 Koln, Germany



have beenmainly utilised for groundwater management, recharge, aquifer protection, groundwater flooding, archaeological assessment and planning. Many of these models have focussed on important aquifers such as the Chalk, and the Sherwood Sandstone.

In 2007 the BGS embarked on a three year R&D project to extend the use of the GSI3D software and methodology to most styles of bedrock geology, notably faulting (normal, reverse, strike-slip, scissor, thrusts etc), folding, intrusive and cross-cutting bodies and overturned strata. Initial results from this development are presented from the London and Plynlimon (Central Wales) testbeds (Figure 2). It is hoped to roll out a beta version of the new GSI3D bedrock software to early adopters in spring 2009.

Customers can obtain GSI3D-built models in several ways. Geological models can be served via the web in form of Flash animations and 3D PDFs giving the users a preview of the model and some interactive functionality. BGS also uses a Java based 3D viewer that forms a subset of the GSI3D software called the Subsurface Viewer. This will be shortly replaced by a bedrock enhanced version to be called the LithoFrame Viewer. In these viewer applications the user can create synthetic boreholes and sections, change the theme properties of the model, create contour maps as well as explode the model for detailed analysis. These calculations are performed on the user's PC so only the data has to be transmitted via the web or CD-ROM. Data can also be delivered to customers in many other requested formats such as scattered x,y,z points, ASCII grids, ESRI shapes and grids and VRML surfaces.

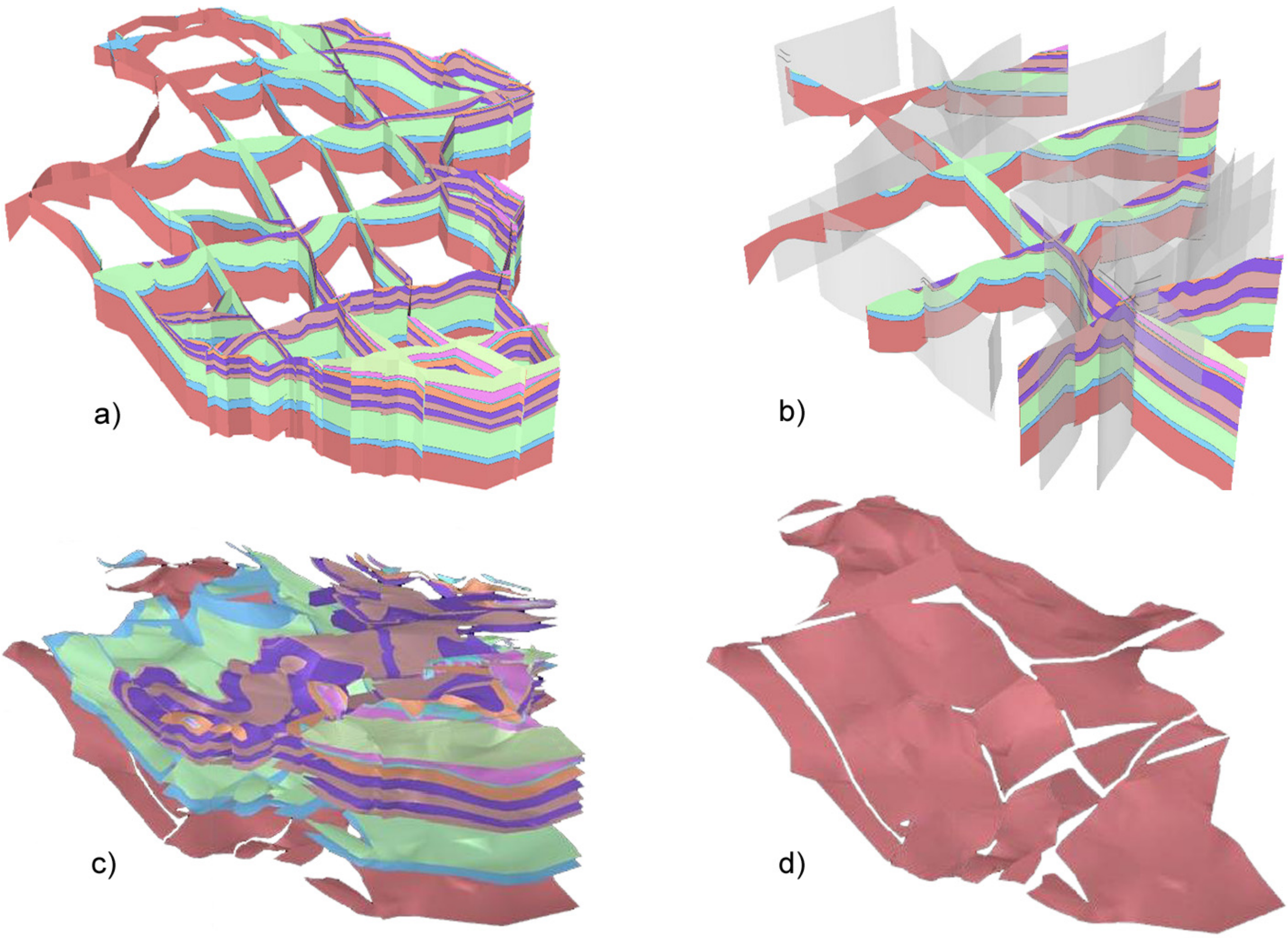
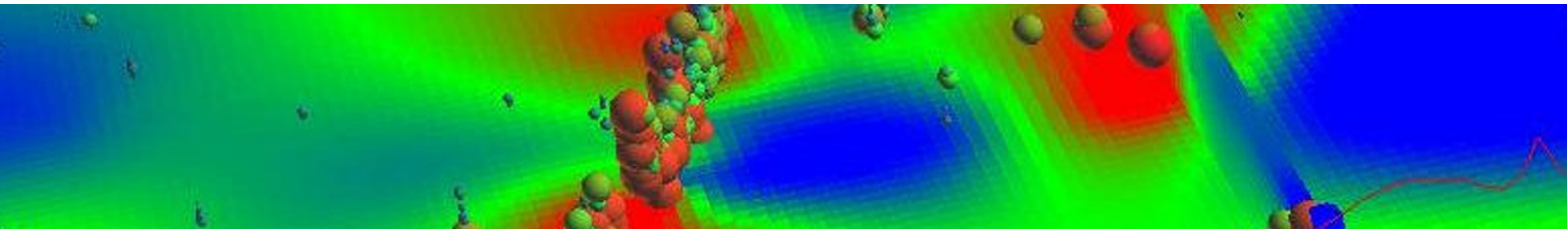


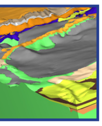
Figure 2 The Plynlimon testbed for bedrock modelling: a). Complete fence diagram showing folded Lower Palaeozoic strata. b). Faults in transparent grey together with selected sections from the fence diagram. c). Calculated basal surfaces. d). Single faulted basal surface showing normal, reverse and scissor faults.

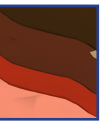


Unlocking the potential of digital 3D geological subsurface models for geotechnical engineers

Keith Turner[1], Holger Kessler[2] and Martin Culshaw[3]

The successful execution of large and complex underground construction projects in urban areas increasingly depends upon a precise definition of subsurface conditions. Geological conditions dominate the cost and feasibility of these projects. Over the past two decades, a series of sophisticated 3D modeling technologies have been developed, but their routine application to shallow subsurface geotechnical site investigations has been limited.





Geotechnical engineers require 3D geological subsurface models that accurately portray the spatial geological framework and contain appropriate information concerning geotechnical characteristics of all geological features. For projects at the regional assessment or preliminary planning and design stages, these models primarily serve as a communications tool, thus uniform property values may be assigned to individual geological units, and the models can be economically developed using simple model-building approaches. In contrast, projects at the more detailed site investigation or project design stage require a detailed understanding of the natural variability of frequently complex geology and assessment of the spatial variability of specific geotechnical properties based on data from samples and direct observations.

Because 3D geological subsurface models of value to geotechnical engineers during detailed site assessment must define the spatial variation of selected geotechnical parameters and geological processes within the subsurface, creation of these models requires two stages:

- development of a suitable geometric representation of the fundamental geological 'framework' (Figure 3), and
- subdivision, or 'discretisation' of this framework to define and predict the spatial variability required for prediction or numerical modeling (Figure 4).

Because prediction has an extrapolative rather than interpretive character, it thus involves risk and uncertainty, but yet it forms the basis of all decision-making. The 'customers' of these geological models require supporting visualisations and interpretations, which largely depend upon sophisticated visualisation and information-management tools. Although integration of these components for geotechnical engineering projects is not yet common, limited initial experiences suggest the potential for large economic, environmental, and engineering benefits.

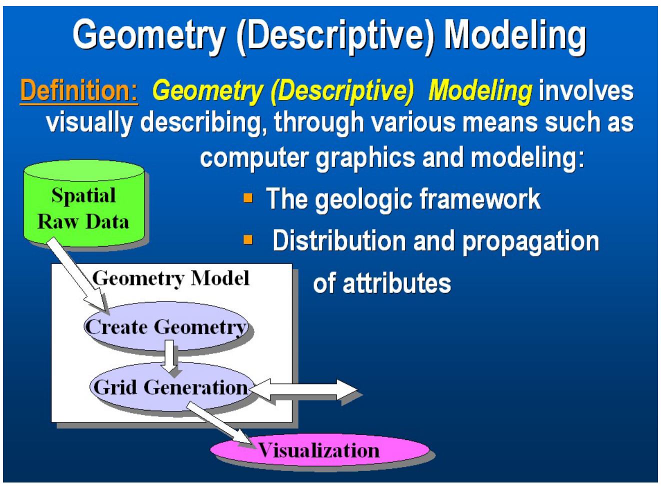


Figure 3 Stage 1 in 3D geological modelling; defining the geological framework.

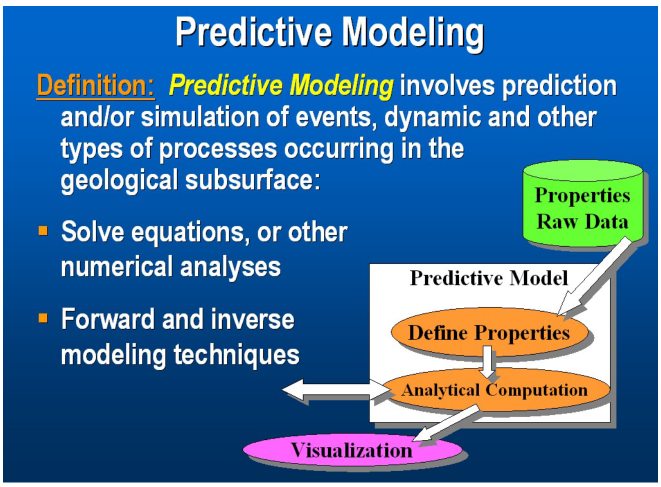
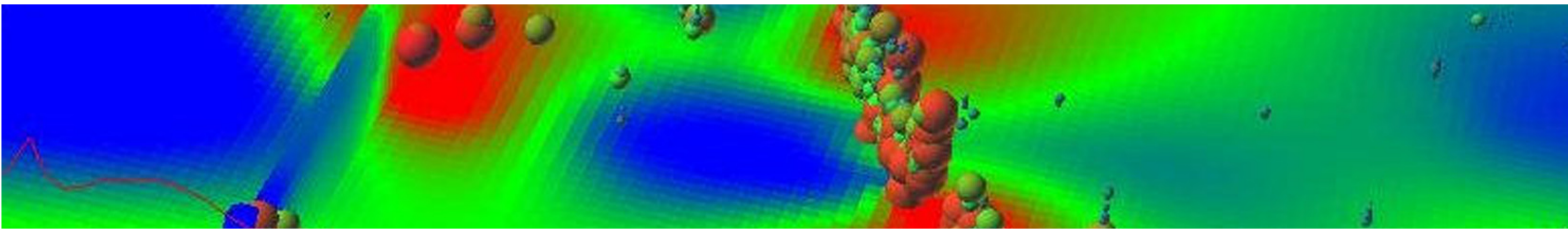


Figure 4 Stage 2 in 3D geological modelling; prediction of properties or processes.

[1] Colorado School of Mines, Golden, Colorado, USA, [2] British Geological Survey, UK, [3] University of Birmingham, UK



Application of BGS 3D modelling to regional groundwater resource studies

Keith Seymour[1] and Martin Shepley[2]

For over 10 years the Environment Agency has been realising the benefits of the BGS's geological knowledge and datasets when carrying out regional (aquifer scale) groundwater resources investigation and modelling projects. A series of examples from the north-west and Midlands regions will be presented to illustrate the way the working relationships have evolved and how the different BGS outputs have helped refine the conceptual understanding and numerical modelling of our major aquifers.

The first real example was the use of structural contours of the top and base of the Sherwood Sandstone Fylde aquifer in central Lancashire, derived from seismic data. The enhanced understanding and representation of aquifer thickness and fault patterns proved key to developing a credible model that is used for water resources management.

The significance of faulting in bedrock hydrogeological responses to abstraction pressures has become apparent in subsequent studies within the Mersey Basin and East Midlands and East Yorkshire Sherwood Sandstone aquifers; BGS 3D respresentation of the bedrock geological structure has proved invaluable in increasing confidence in the conceptual models and formed a basis for testing these in the numerical models.

Similarly, recognising the importance and complexity of drift cover in controlling recharge to, discharge from and the vulnerability of our sandstone aquifers (for example Figure 5), the application of the GSI3D model outputs to regional studies has changed from being best practice to the norm. Bespoke outputs such as hydrogeological domain maps have been developed and refined as 'fit for purpose' products.

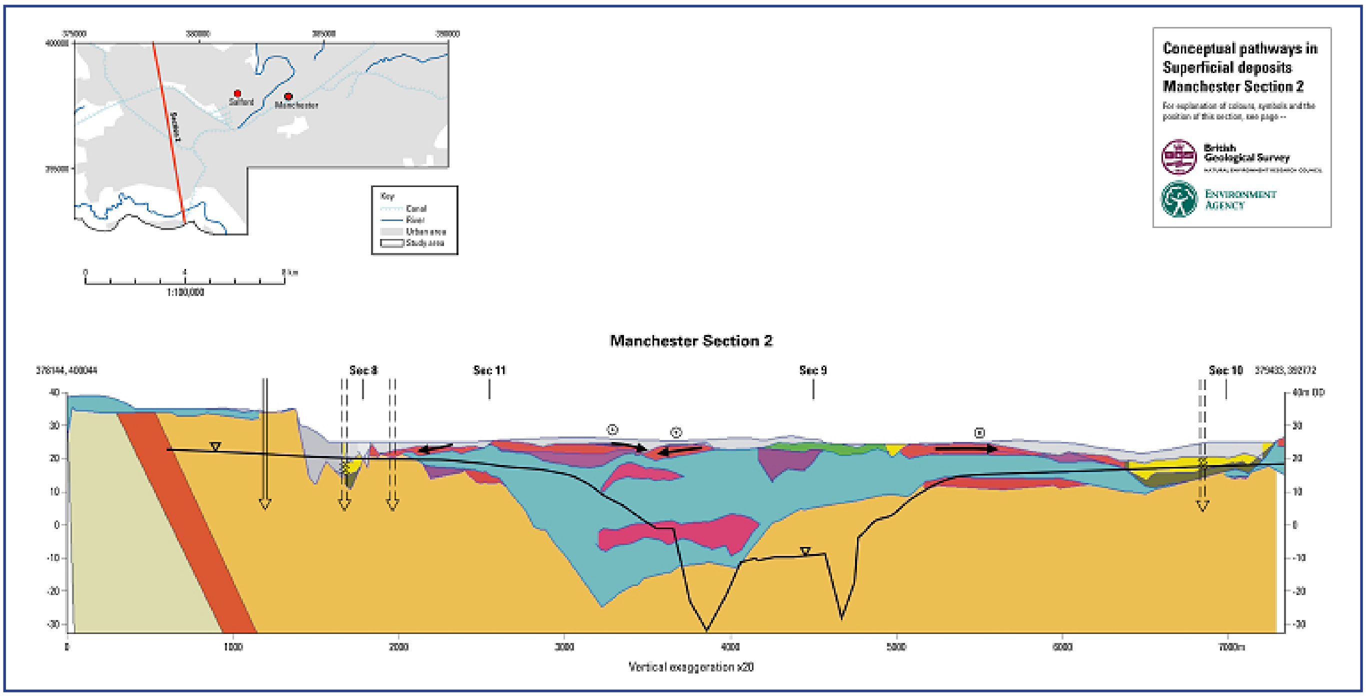
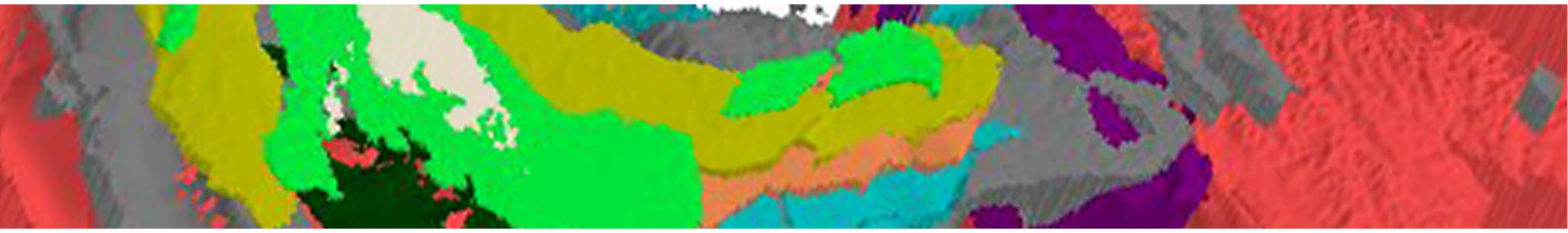


Figure 5 GSI3D constructed section showing flow pathways and recharge from the EA Manchester urban study.

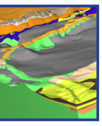
[1] Keith Seymour, Environment Agency - North West Region, Warrington, UK, [2] Martin Shepley, Environment Agency — Midlands Region, Solihull, UK

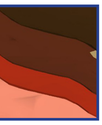


3D modelling and visualisation of digital geoscientific data as an aid to land-use planning in the urban environment: examples from the Thames Gateway and their limitations

Kate Royse[1], Don Aldiss[1], Ricky Terrington[1] and Jon Ford[1]

The Thames Gateway development zone is the biggest urban development project in the UK for over 50 years. Planners need to understand the implications of such large-scale urbanisation on the environment, while requirements for sustainable growth within the Thames Gateway region mean that developers are increasingly being required to demonstrate that proposals are based on sound scientific information. This has resulted in a growing demand for geo-environmental information provided in an accessible, relevant and understandable manner.





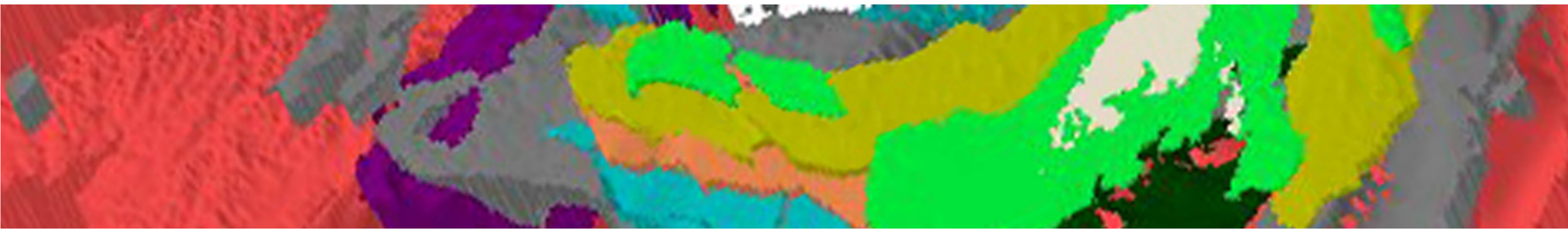
Advances in 3D modelling software and GIS techniques have revolutionised the way that geoscientific data can be displayed and interpreted. They allow urban geoscientists not just to provide raw geological data but also to produce integrated geoscientific information in forms suitable for land-use planning (Fig 6). The new modelling systems can produce attributed 3D geological models showing variation in rock and soil properties, including physical, chemical or hydrogeological parameters. Such models can be used to help provide solutions to many geo-environmental problems encountered during the planning process. Using 3D geological modelling, conceptual ground models are becoming more realistic, with better integration and visualisation of ground investigation data.

With changes in legislation increasing the importance of geo-environmental information, land-use planners are now required to consider the impact that large-scale development will have on the environment. Land-use planners are willing to use geoscientific data but require geoscientists to make it more accessible, relevant and understandable than in the past. The traditional geological map is no longer an appropriate medium in which to present geo-environmental information. On the other hand, geoscientists have learnt that it is only by understanding a client's individual needs for appropriate customised data outputs is it possible to ensure that geoscientific data will be used within the urban planning process.

There are still (at least) three major issues to be resolved. Firstly, geoscientists must effectively communicate the limitations of the interpretations on which they base their assessments, so that sound judgments can be made. This is becoming more critical as improvements in 3D modelling techniques allow models to appear more realistic, and so apparently more reliable. It is essential, therefore, that planners can differentiate between observations and interpretations, and can understand the inherent uncertainty of a digital 3D model and the geoscientific datasets on which it is based. There are still difficulties in the presentation and visualisation of uncertainty assessments.

The second issue is the ability to represent easily the variability within geological units. Currently, attributed 3D geological models such as those presented here display the bulk attributes of a particular unit. If the data are available, the geological units can be subdivided to show stratiform variation but even where data exists it is difficult to display non-stratiform variation of a given parameter within a modelled unit. Future work should focus on ways of representing property variation which is both realistic and

[1] British Geological Survey, UK



understandable to land-use planners. These issues will need to be addressed if an uptake of digital geoscientific models and data is to be realised.

Finally, efficient dissemination is key to the large-scale uptake of digital geoscientific data and 3D models within land-use planning. At present it seems that this will depend on the continued development of the Internet as a medium for data transfer and sharing. Web-enabled platforms such as Environmental Information System for Planners (EISP), which are already being developed, will allow land-use planners to access geo-environmental information directly from the Internet. A future is imagined in which the characteristics of a development site, such as its geology, geography, past land-use and data on existing developments, can be displayed in a virtual world, generated on a web-based platform, so enabling developers to visualise the impact of their proposed projects from the comfort of their desk top computer.

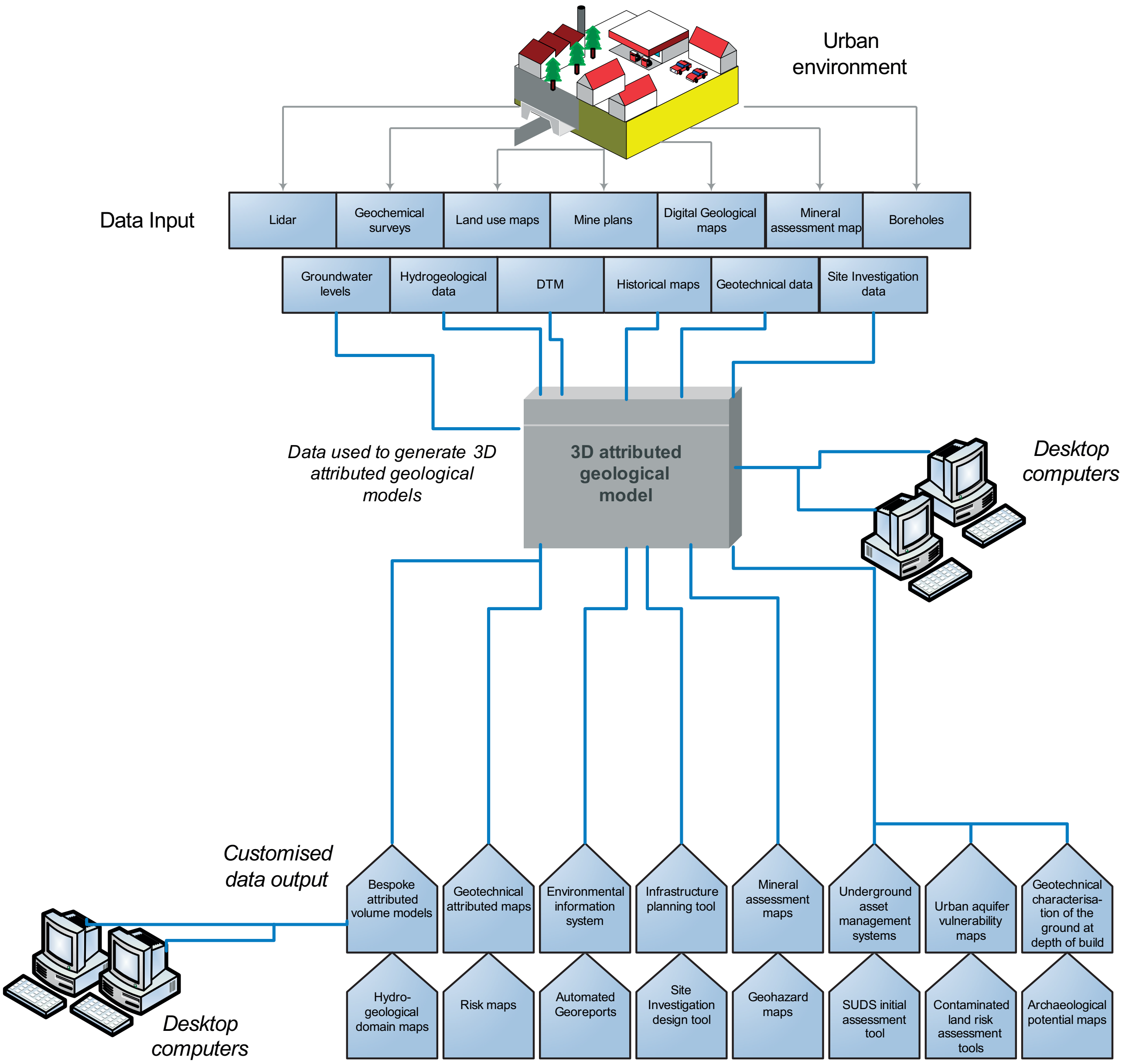
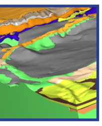


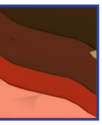
Figure 6 Flow diagram showing the process of building and attributing the 3D geological model.

The 3D geological and anthropogenic history of the Mersey Corridor

Simon Price[1], Ricky Terrington[1], Helen Burke[1], Dick Crofts[1] and Steve Thorpe[1]

The places where we live, work and interact with our environment on a daily basis are changing. Our major cities are evolving and regeneration is improving the quality of life for communities across the UK. It is critical to characterise the processes and environmental impacts of urbanisation to ensure the sustainable development of future towns and cities. Given future social, economic and environmental scenarios, development today should meet the needs of future communities whilst minimising its environmental impact. The role of urban geoscience is to provide an integrated environmental science framework that improves quality of life, mitigates hazards and promotes economic growth. It can also inform future adaptation strategies for urban communities in response to climate change scenarios.





Large scale redevelopment is taking place within the Lower Mersey Development Zone. This major regeneration zone comprises the urban areas of Manchester, Warrington, Runcorn, Widnes and Liverpool. Importantly, the area includes major conurbations that have developed along formerly strategic coastal zones that are now the focus of rapid regeneration. Salford Quays will be home to MediaCityUK, one of the largest multimedia centres in the world and the new home of the BBC. To ensure the safe and sustainable regeneration of major towns and cities within the Mersey Basin and to reduce subsequent risks to people and property, there is an ever-increasing demand for integrated geo-environmental information. This information can be disseminated in 3D to provide an environmental framework for sustainable decision-making and land-use planning in urban environments.

Multidisciplinary, 3D environmental science within the Lower Mersey Development Zone has investigated the role of people and anthropogenic processes and environmental impacts as a major factor in urban development. The magnitude and frequency of anthropogenic processes and their impacts are governed by a range of environmental, economic and social factors. All contribute the evolution of urban landscapes both inland and along the coastal zone. Rapid industrial development in north-west England resulted in a legacy of potentially contaminated artificial ground that has resulted in highly variable ground conditions. Our 3D modelling has revealed the pattern of deglaciation at the end of the Devensian associated with the retreat of the Irish Sea ice sheet. The integration of attributed anthropogenic, natural superficial deposits and bedrock 3D models provides high resolution 3D framework to aid environmental decision-making. It provides a basis on which to quantify future environmental change in urban areas.

Dissemination in 3D allows users to easily interpret, analyse and apply 3D ground information to meet their needs. The urban scientific research strategy in north-west England is strongly focused towards collaboration with users to ensure that environmental data and information is fit for purpose. The Environment Agency has applied the derived outputs of 3D geological models to meet their legislative requirements within the Water Framework Directive as the area overlies the Sherwood Sandstone aquifer.

Multidisciplinary urban research within north-west England will develop the 3D environmental framework towards integration with economic and social sciences. It is essential that the social and natural sciences are integrated to ensure that the objectives of sustainable development are met. Sustainable urban development can only take place if the interactions between people and the environment are understood.

[1] British Geological Survey, UK

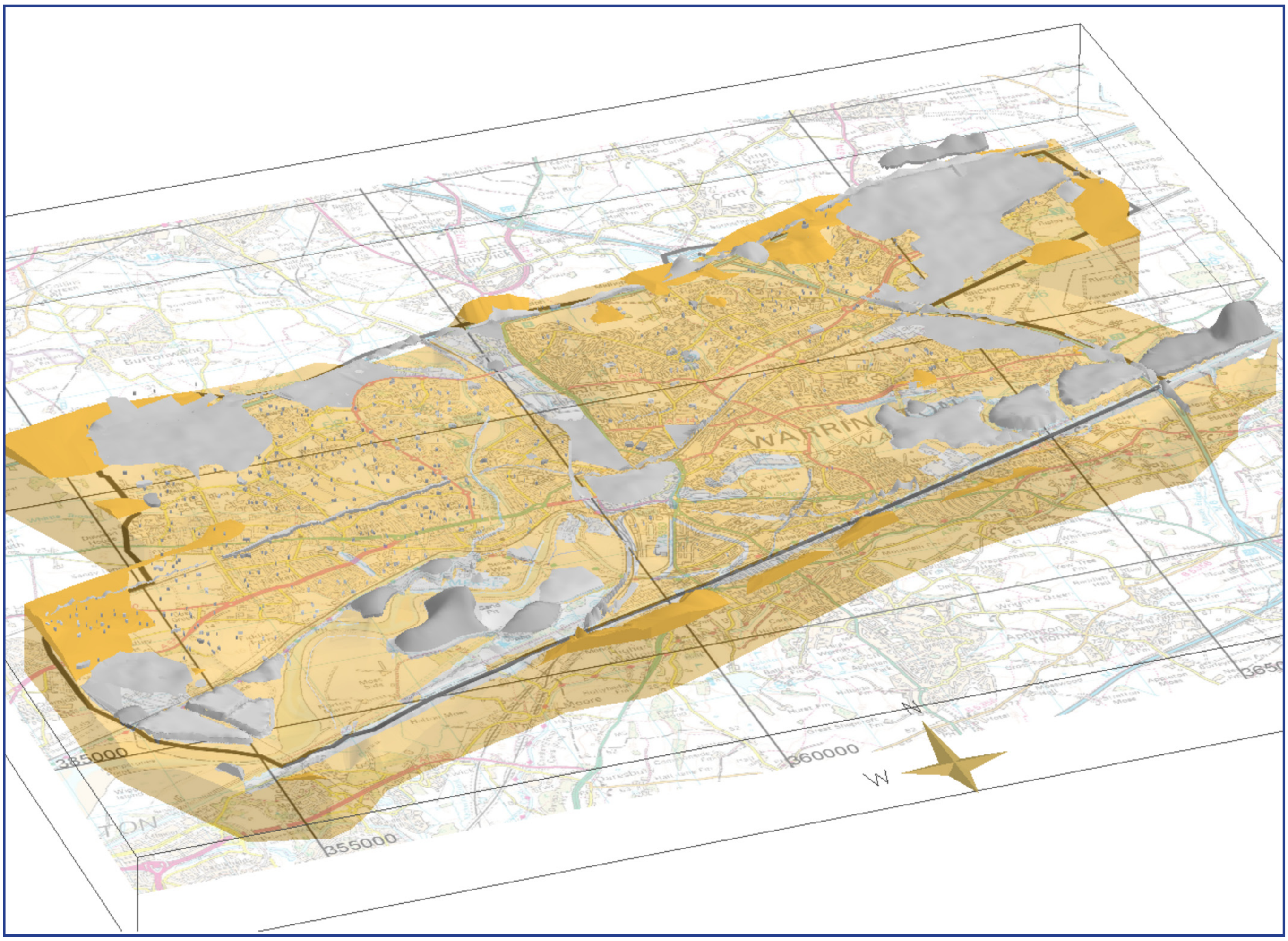
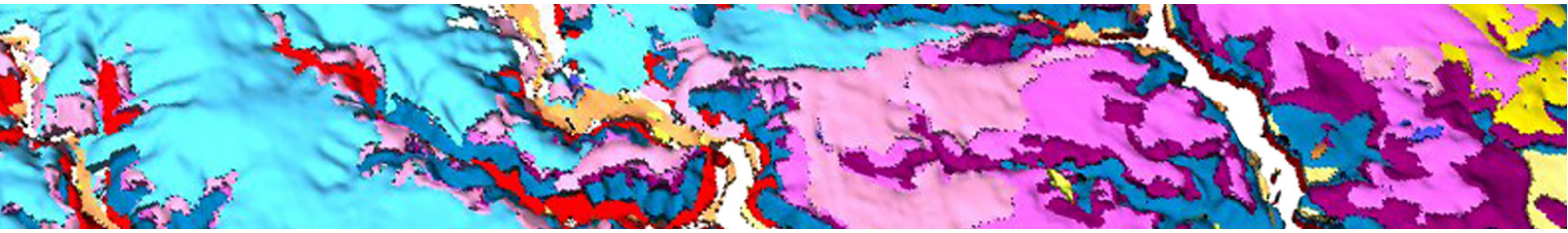
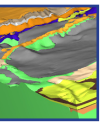


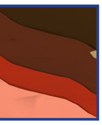
Figure 7 High-resolution 3D model (GSI3D™) showing areas of artificial ground (in grey) including infilled pits, quarries, waste tips and canals overlying Sherwood Sandstone aquifer in Warrington, north-west England. Artificial ground represents the impact of a range of complex historical anthropogenic processes and is a major process in urban landscape evolution.



The comprehensive geological 3D subsurface model as a standard tool for addressing questions on water management

Egon Harms[1] and Michael Howahr[2]





The water supply in the north-western part of Lower Saxony is provided largely by the abstraction of groundwater from Quaternary and Tertiary porous aquifers. The main features of the geological formation, the structure of the individual groundwater levels and the distribution of the superficial deposits are generally understood although there is often no uniform interpretation of the heterogenous subsurface data which has been collected over decades. In the past, an exact understanding of the stratigraphy and sedimentology of the Cenozoic sequence was impossible However, against the background of sustainable water management and the requirements placed on modern water-supply companies, a detailed knowledge of the geological subsurface is absolutely essential.

An integrated 3D model that brings together all subsurface information and therefore describes both the lithology and the hydrogeology is able to resolve this difficulty. Water suppliers need a regional geological 3D subsurface model which is sufficiently exact and directly applicable for water management planning and in addition new solutions are needed for other specialist areas (engineering geology, resource security, ecology, agriculture).

Since 2004, the Oldenburg-East Frisian Water Board (Oldenburgisch-Ostfriesische Wasserverband, OOWV) has created extensive geological 3D models covering the water catchment areas and uses these for all questions relevant to the subsurface geology. The subsidiary company NOWAC GmbH has set up, and looks after, the 3D models for the OOWV and offers this and other services concerning the subsurface to other water supplies in the region.

Methodology

The geological models introduced here were developed by processing geologists using the integrative software GSI3D. The GSI3D methodology is based on the construction of close-meshed geological cross-sections and the definition of distribution boundaries for all model units found in the sections.

With the help of the software, all significant surface and subsurface data capable of being digitised and geo-referenced such as boreholes, geophysical and geochemical investigations, geological (among other) maps, contour and isopach maps and DTM data could be integrated in the course of iterative section construction. In addition, the emerging models were complemented with old analogue hand-drawn sections and in some cases with already existing 3D data such as Gocad-TINs, ESRI-, Surfer- and GeoObject-Grids (ascii) etc. All of the input data described and the digitised results from old surveys could, for the first time, be interpreted together within a three-dimensional context and tested for plausibility before being processed into the emerging model.

From the information of the constructed cross-sections and the associated unit distributions (envelopes) geological bodies were calculated for every model unit that are consistent with all the available surface and subsurface data.

Since 2003 there have been GSI3D-constructed models for the Weser-Ems region with a total expanse of about 3700 km^2 (Figure. 8). They are based on a consistent network of close to 1000 individual geological cross-sections in which over 10 000 boreholes and 1700 geoelectrical measurements have been incorporated.

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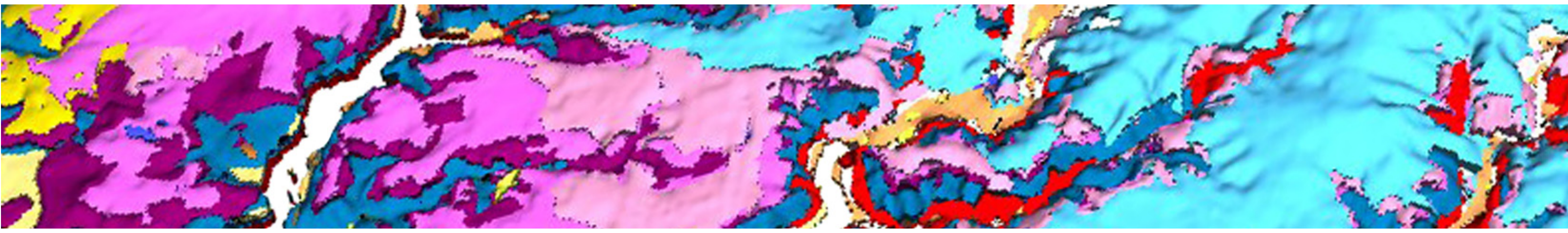

The methodology described here for 3D subsurface mapping, is also used by the British Geological Survey (BGS) for geological surveying, and is also described in Howahr (2003) and Schade (2003). In Germany, the OOWV uses GSI3D as the standard methodology for the surveying of the subsurface geology needed for water management.

Model attribution, appraisal and application

With respect to the classification and lithology of the individual model units, these are essentially based on the nomenclature of the existing maps of the Geological Survey of Lower Saxony (LBEG). The genetic-lithostratigraphic structure models were converted to hydrostratigraphic 3D models using an additional attribution in accordance with Reutter (2005). On the basis of this system, the detailed model data can be translated directly and without loss into a discretisation schema of a 3D groundwater flow modelling via a data interface. The hydrogeological rock parameters determined in the course of subsurface modelling were correspondingly added in at this stage.

Additional model attribution relating to aspects such as geothermal properties, raw materials, engineering geology etc. have also been achieved. In accordance with the associated attributes, a large number of outputs can be exported from the model data for a variety of different purposes. These include vertical and horizontal sections, virtual boreholes, thematic maps, contour and isopach maps (surface and subsurface, thicknesses) and volume calculations.

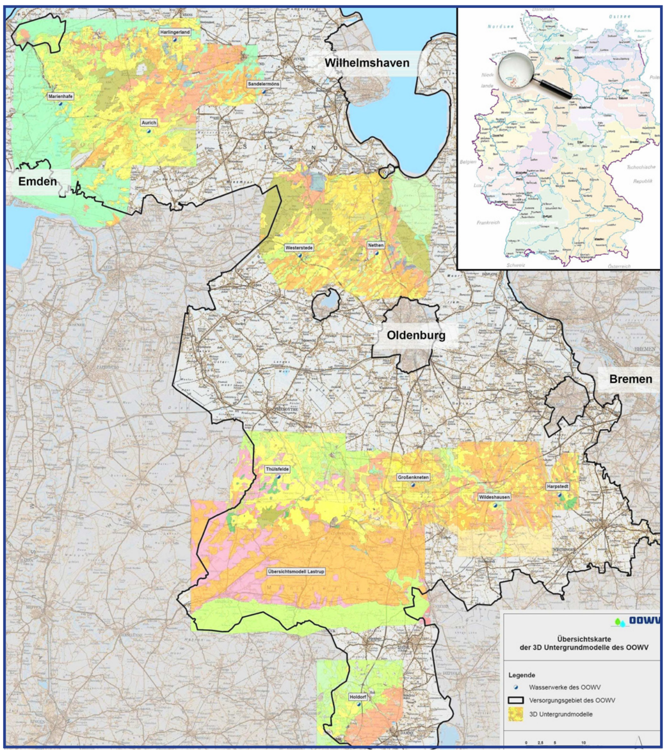

Figure 8 Distribution of geological 3D models in north-western Lower Saxony (Germany).

In order to deal with questions on groundwater protection, the standardised superficial layer evaluation system of Holting et al. (1995) will in the future be applied to the unsaturated zone of the subsurface model. The 3D subsurface model supplies the necessary evidence base for this evaluation system.

The (hydro)geological 3D model in the daily operation of water management

In the last few years, the OOWV has developed the (hydro) geological 3D subsurface model into a standard tool for daily water management. Using a platform-independent display and analysis software, it is also possible for non-specialist technical staff to assess complex subsurface situations and where necessary, to apply appropriate measures.

Through the direct access to the information and data sources, '3D subsurface models' were able to decisively influence numerous water rights and conservation area procedures, groundwater protection measures and extensions of monitoring point networks.

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Building a 3D model of the south Sirte Basin, Libya: integrating GSI3D with GOCAD and ArcGIS

Andrew Newell[1] and Ian Gale[1]

The aim of this task was to build a 3D model of post-Eocene strata in the southern Sirte Basin, Libya. The client was BG Libya who required a source of water for drilling oil wells within a block measuring 100 km by 60 km. The primary sources of information were BGS maps and reports on the geology and hydrogeology of the Sirte Basin from the 1970s. The BGS was working in collaboration with Nippon Koei UK Co Ltd who provided just six days to complete the task. Six surfaces in the post-Eocene succession of shallow marine sands, clays and carbonates were modelled.

Borehole data were available only in the form of labelled values on contour maps within the reports (Figure 9). Extracting this information required the scanning and georeferencing of maps using geographic coordinate system WGS 1984 in decimal degrees.

NASA SRTM (Shuttle Radar Topography Mission) was used as the terrain model. SRTM has 90 m grid spacing, near global coverage and is freely available from the internet. The vertical accuracy is within ± 10 m.

GSI3D cross-sections were then constructed in the conventional way using the borehole records that had been 'reverse engineered' from borehole names and formation bases distributed across many maps (Figure 10). All borehole records and contours were projected to UTM Zone 34N (WGS 1984) for export to GSI3D.

XYZ points for each formation base were exported from GSI3D cross-sections to GOCAD and triangulated using discrete smooth interpolation. Surfaces were imported back into GSI3D for solid modelling and export to a self-executable viewer file which was handed to the client on project completion. (Figure 11).

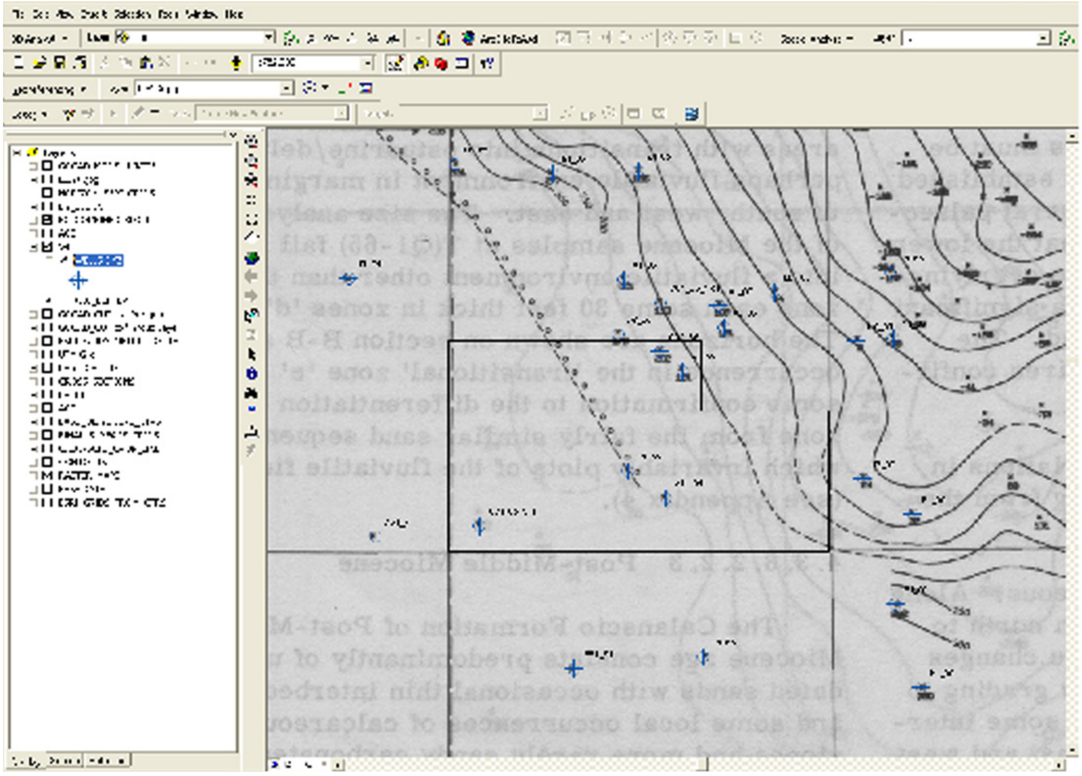


Figure 9 Georeferenced contour maps displayed in GSI3D.

[1] British Geological Survey, UK

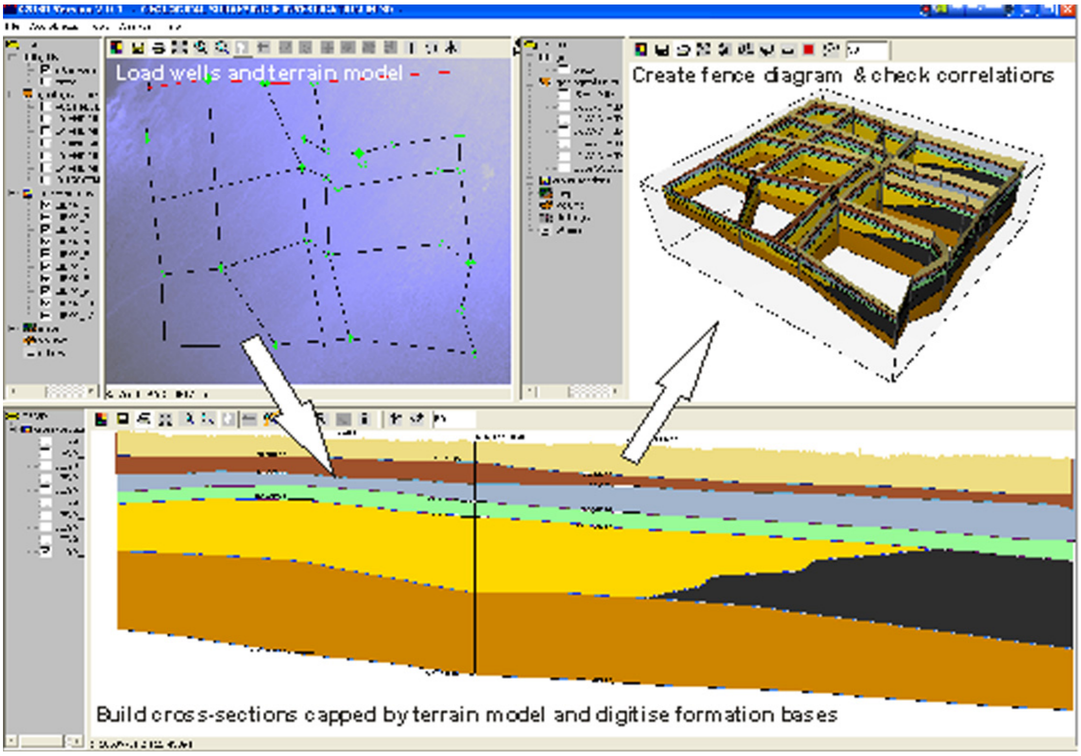


Figure 10 Fence diagram construction in GSI3D.

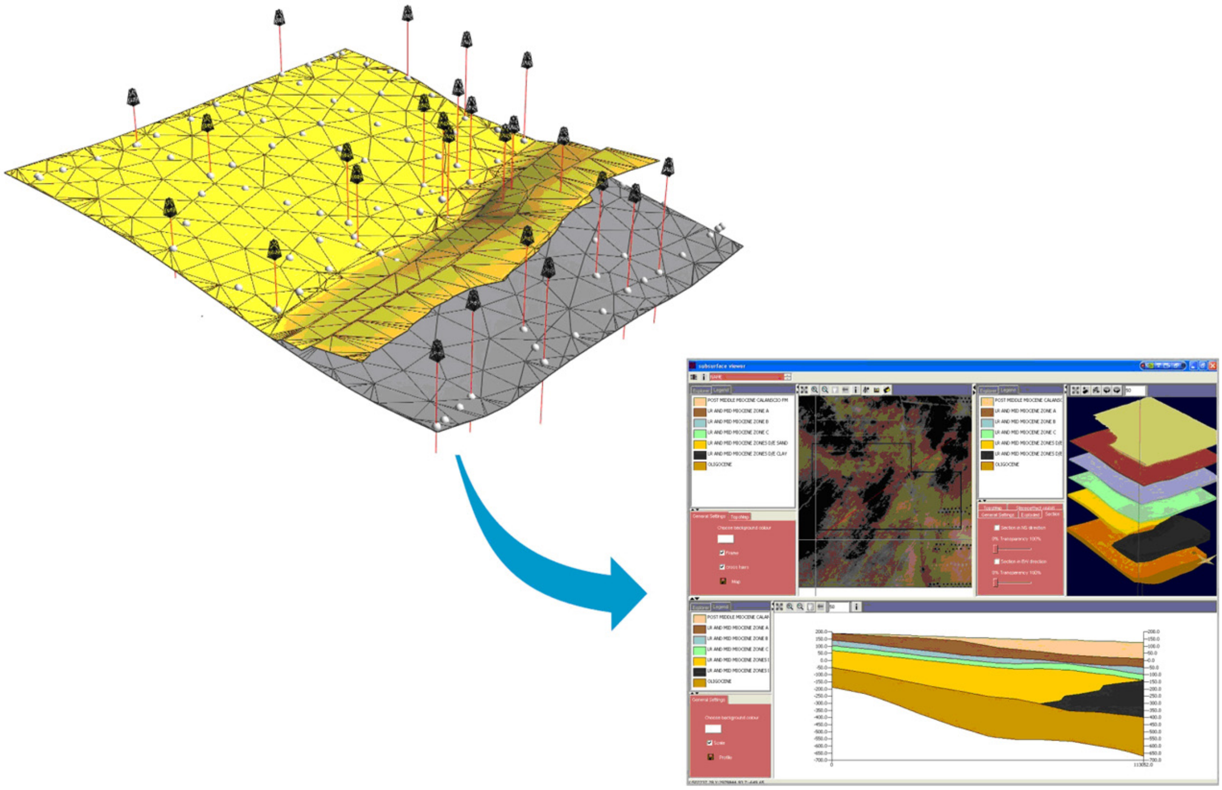
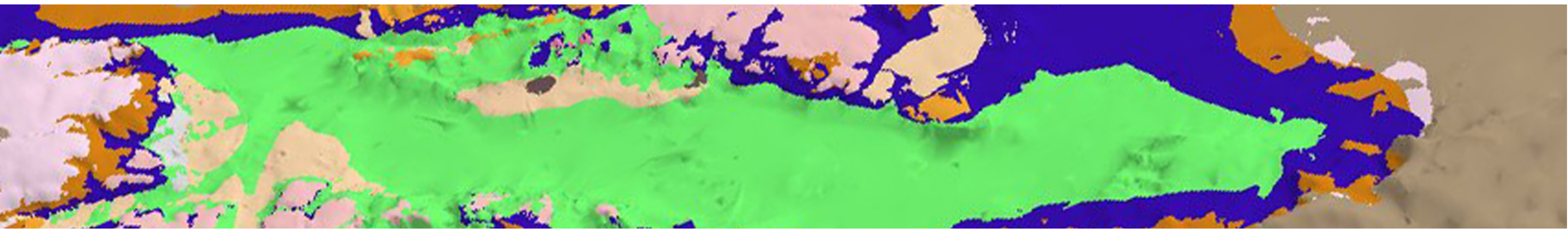


Figure 11 Triangulated surfaces in GOCAD exported to the Subsurface Viewer for delivery.



The 3D geology of London and the Thames Gateway: a modern approach to geological surveying and its relevance in the urban environment

Jon Ford[1], Helen Burke[1], Steve Mathers[1], Kate Royse[1] and Ricky Terrington[1]

As a provider of geological advice to industry, academia and the public, the British Geological Survey (BGS) has recognised the need to change the way it presents geoscientific information, resulting in the construction of attributed 3D geological models. The need to deliver 3D modelling solutions is of great importance in urban areas, where geological factors play a major role in supporting ground investigations and sustainable water management studies. The 3D geological model of London and the Thames Gateway occupies an area of approximately 3200 km^2 and extends to a depth of 150 m. It includes a total of 38 units, ranging from artificial deposits and Quaternary sediments down to Tertiary and Cretaceous bedrock. The model is built using existing geological surveys, DEMs and extensive borehole and site investigation data. Modelling was carried out using GSI3D (geological surveying and investigation in 3 dimensions) software. This software and its associated workflow produce a series of gridded volumes of the geological units, constrained at depth by a network of cross-sections constructed by the geologist. The Thames Gateway model was attributed by assigning property values to each geological unit. This has provided a way of visualising the spatial relationships between geological units with differing properties. The model has revealed previously unrecognised geological information. Further benefits of the attributed model include the ability to visualise and appreciate the link between lithology and physical characteristics. Such models will produce the decision support system necessary for the sustainable development and management of today's megacities.

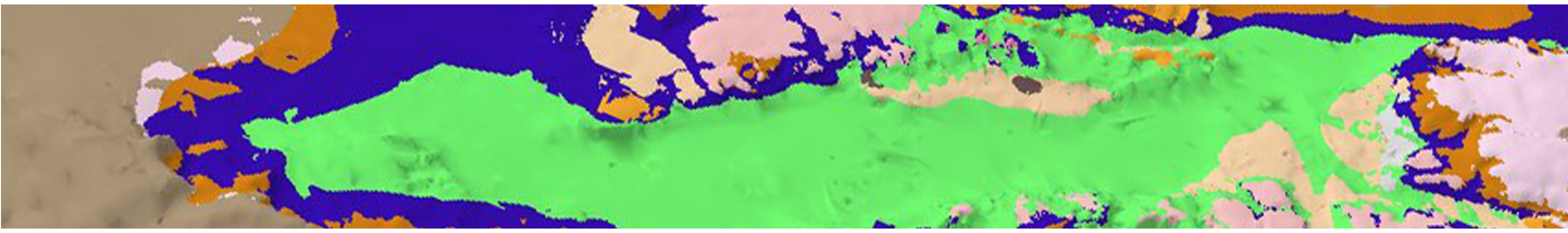
Modelling in the London area has been completed for a variety of strategic scientific and commissioned projects, each fit for purpose at a range of scales.The earliest GSI3D model in the London area was comissioned by local authorities in 2002 to provide a decision-support tool for the sustainable management of aggregate extraction and archaeological preservation. This model shows artificial ground and a subdivision of the superficial and bedrock succession down to the top of the Chalk Group. This work was extended and refined over subsequent years to cover the whole Thames Gateway Development Area. The Thames Gateway model is built from over 4000 boreholes and over 200 north–south and east–west trending cross-sections The model includes a detailed subdivision of artificial ground, Holocene deposits and selected bedrock units. The Thames Gateway model is commensurate with geological mapping at a scale of 1:10 000 (Figure 12).

A second modelling initiative, the London LithoFrame50, extends model coverage to the Greater London area. This strategic model is based on over 6700 line-kilometres of correlated cross-sections, it includes a total of 38 units down to the base of the Chalk Group at depths of 200–500 m. Deeper surfaces such as the Lower Cretaceous and top of the Palaeozoic basement have been added to the model from regional studies. This model provides an equivalent level of detail to 1:50 000 scale mapping, and represents the 3D equivalent of the geological map of London covering the four sheets 1: 50 000 sheets described in the recently published London Memoir (Figure 13).

In many parts of these models, borehole data is available in such large quantities that not all records can be used. A review and prioritisation of the available data ensures that the most reliable and representative records are incorporated in the model. Boreholes that are not considered initially can be introduced at a later stage to refine the interpretation.

Further modelling at a larger scale has also been completed. These models provide additional information on the geology of the Thurrock are adjacent to the Dartford Crossing and also the Olympic 2012 site and Lower Lea Valley.

[1] British Geological Survey, UK



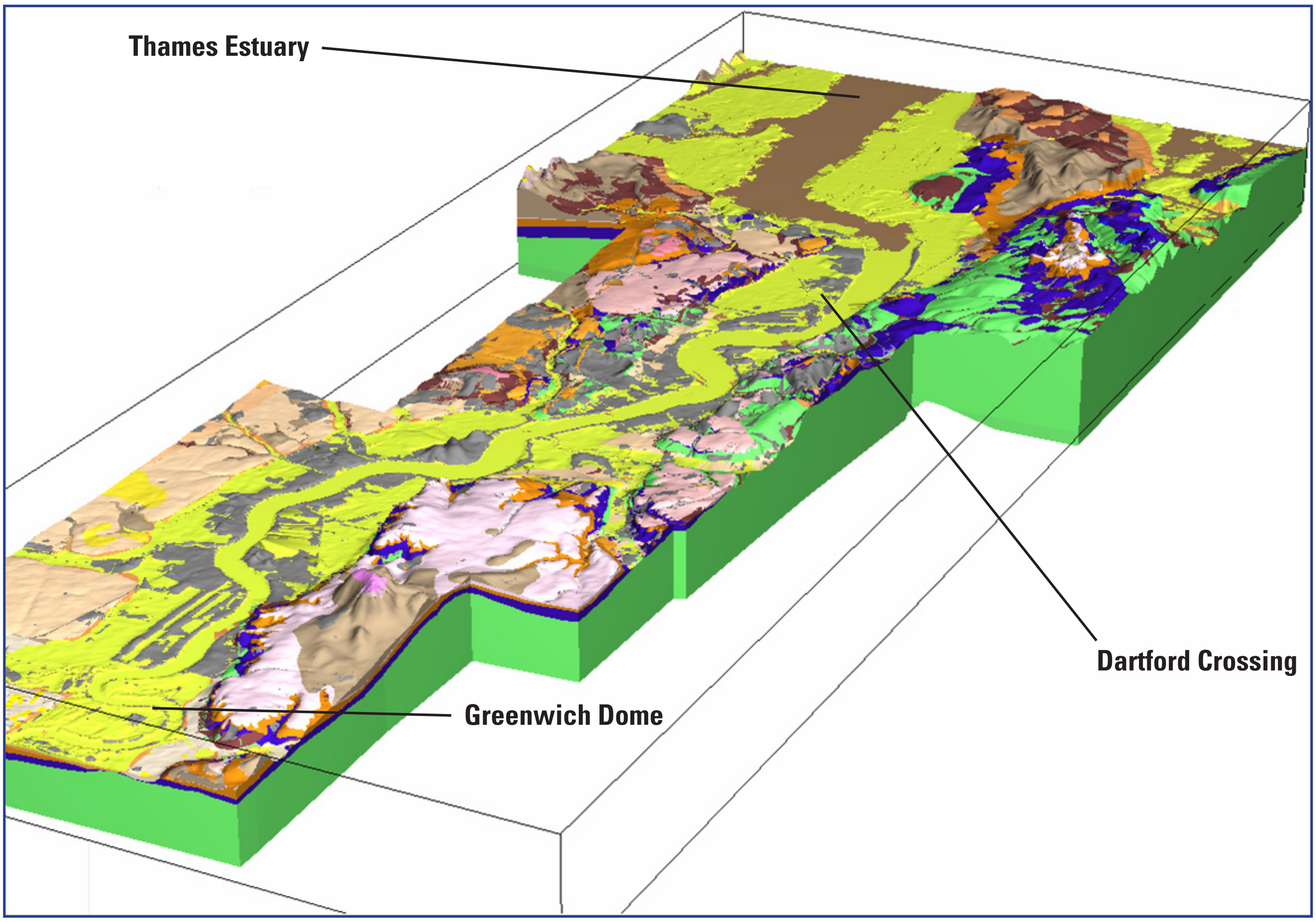


Figure 12 The Thames Gateway model covering 1000 km^2 viewed from the south-west.

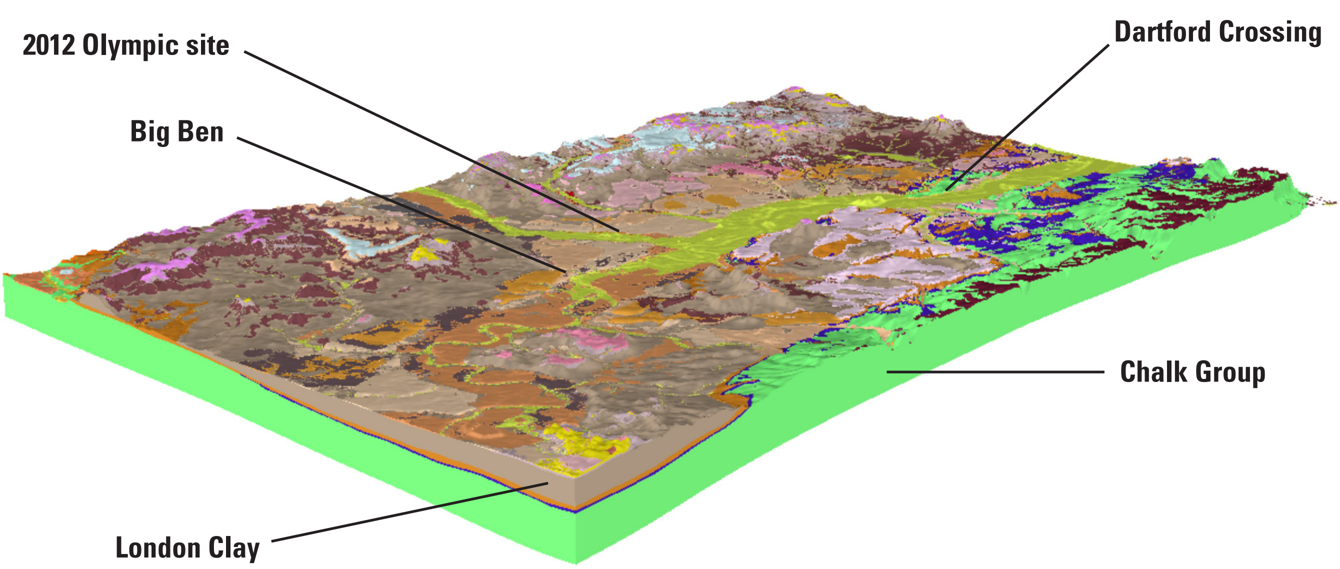
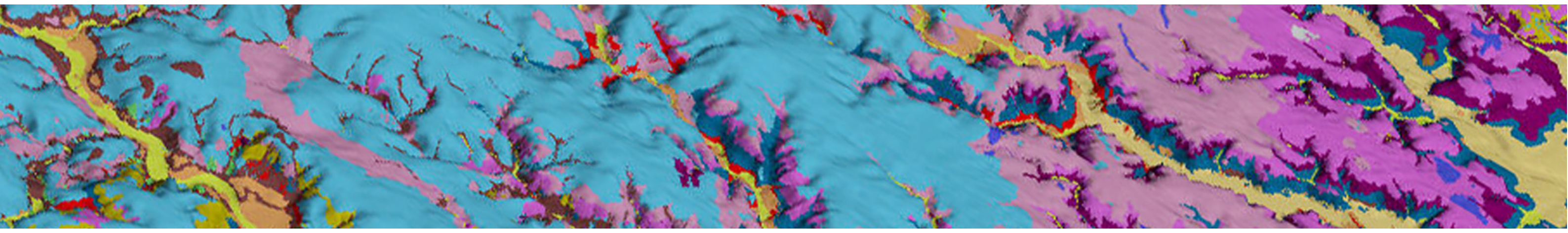


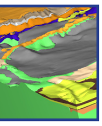
Figure 13 The London LithoFrame 50 model covering an area of 60 x 40 km (2400 km^2) viewed from the south-west.

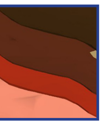


GSI3D and soils — building detailed 3D models of the shallow subsurface

Andreas Scheib[1] and John Williams[1]

The capabilities of GSI3D in constructing bedrock and superficial geological models has been successfully proven and is now the software is a widely used modelling tool within and outside the BGS. With the recently established Sustainable Soils Team, the BGS has focussed its research towards the important thin soil layer blanketing the surface of our planet. Several models are shown to depict ways of displaying the soil layer within geological models.





The principles of soil classification are very similar to how geological units are described and classified. Mapped soil units are described as soil series or groups, depending on scale, and represent the top 1–1.5 m of the subsurface. Vertically, soils are divided into horizons which will differ in properties such as texture, organic matter and colour. Each soil series has a characteristic sequence of vertical horizons and a certain parent material from which it is derived. This sequence enables the soil model and the geological model to be integrated.

To build a soil model in GSI3D two sets of data are needed; a soil (-series) map as *.shp file and vertical augerhole information. The augerhole data should at least contain the thickness of horizons along with horizon codes. A soil surveyor however, will also routinely record information such as texture, Munsell colour, organic and carbonate content and stoniness. This information can also be used to attribute the calculated soil units.

Two different ways of building a 3D soil-geology model are shown:

1) Using only a soil series map. These series represent an average depth of investigation of say 1.2 m. The DTM was therefore reduced by this amount and a calculated a 'soil series volume' model was produced, this is basically a 3D soil series map. Descriptions of clay content and permeability of soil series can also be used to attribute this model. Overall, this is a much simpler way of including a soil layer in a 3D geological model, although it results in the information of the soil within the top 1.2 m being generalised (Figures 14a, 14b).

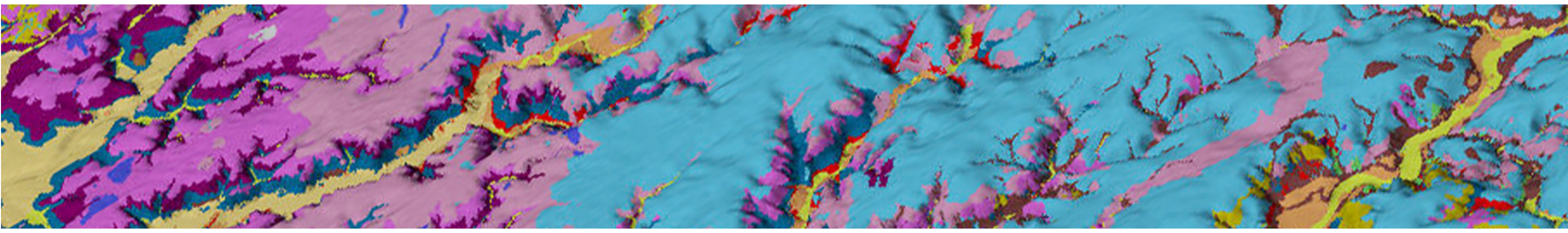
2) Using the augerhole data and soil series map together to construct a 3D soil-horizon model. As soil horizons follow the same arrangement as geological stratigraphy, auger logs can be used in exactly the same way as borehole logs by adding the horizons to the top of the sequence (*.gvs file) and assigning RGB colours (*gleg file). The soil model was built in exactly the same way as conventional geological models, but using augerhole sticks and soil series maps instead to correlate sections and draw horizon envelopes (unit distributions). This approach is much more time consuming, but will result in a much more detailed representation of the soil layers shown here in exploded form (Figure 14c).

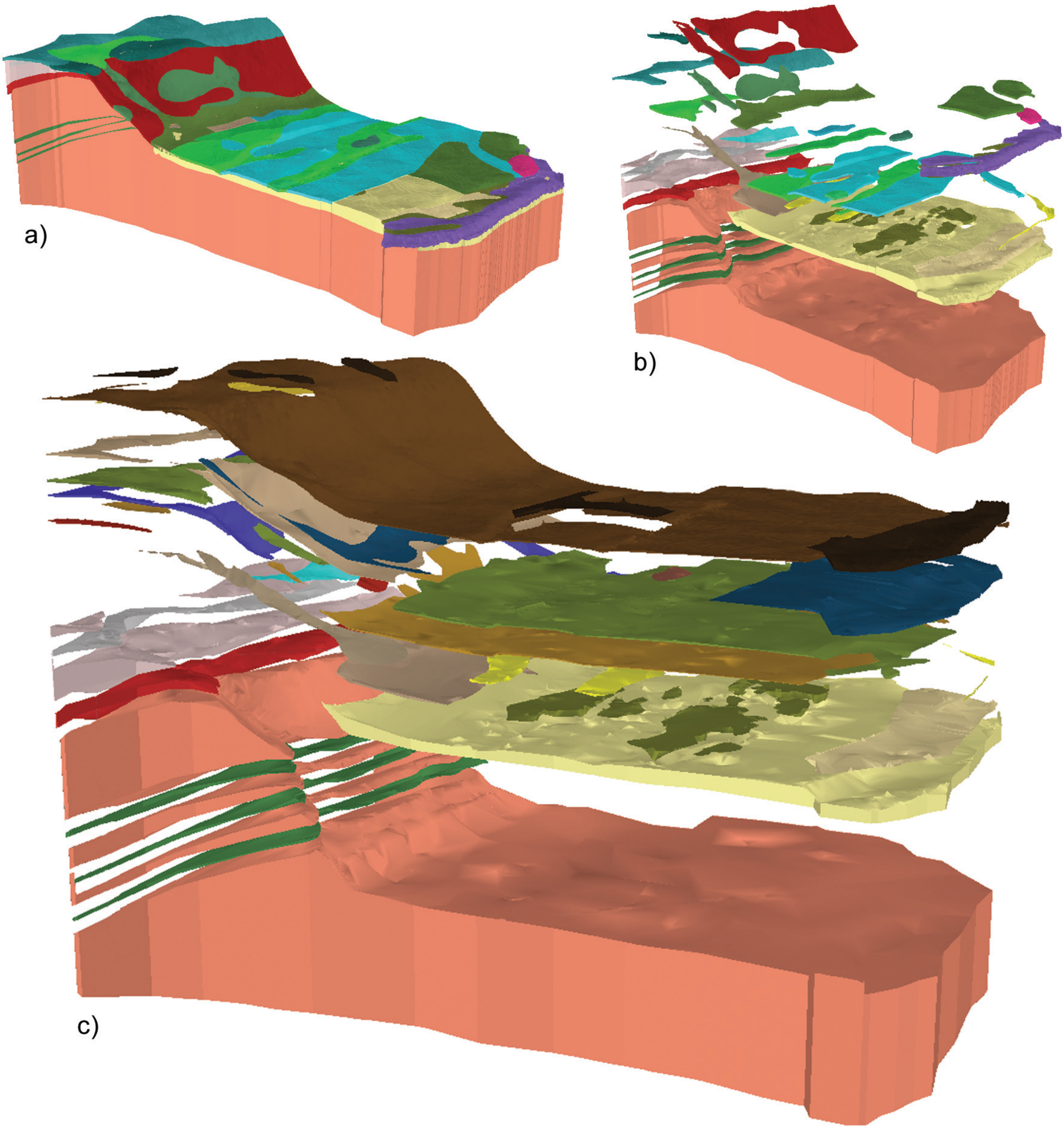
Near-surface geophysical data was also utilised in order to constrain the structural relationships between modelled soil units and their relevant parent materials such as superficial deposits or bedrock. Visualising geophysical datasets in the GSI3D environment allows the user to define the distribution, morphology and extent (in 3D) of soil parent materials, allowing for increased resolution while integrating soil data with geological models in 3D.

There are limitations in the visualisation of soil layers, especially if the model area is larger than one km^2. The calculated soil units and especially horizons will only appear as very thin blankets even when the 3D model is viewed with a large vertical exaggeration (Figure14c).

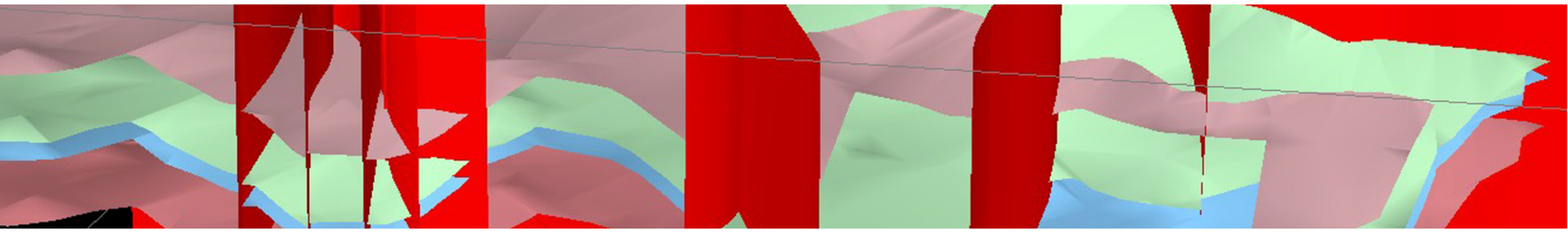
We should consider including a soil layer in models for environmental or hydrological studies where soils play a vital role in decision-making and impact assessments.

[1] British Geological Survey, UK





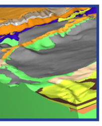
Figures 14 a top left and **14b** top right display the soil-geology model based on approach 1 using the soil series map whilst **Figure 14c** beneath shows the soil-geology model based on approach 2 correlating the 9 individual soil horizons. The models are of the Shelford area in the Trent Valley north-east of Nottingham and cover about 2 km^2; the views have a vertical exaggeration of x10. The bedrock geology comprises Triassic mudstone (pink) with hard siltstone bands in green (skerries) overlain by sandstone (red) and mudstones (pale grey). The superficial deposits are Quaternary river terrace deposits (pale yellow) of sand and gravel within the valley with thicknesses between 3 and 5 m.

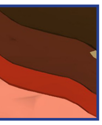


GSI3D modelling in the Vale of York: application of the results and 4D interpretation of the glacial geology

Anthony Cooper[1], Simon Price[1], Jon Ford[1], Helen Burke[1] and Holger Kessler[1]

The geological understanding of the Quaternary deposits of the Vale of York has been built up from numerous datasets. It has been aided by interpretation of digital elevation models (DEMs), allied with air photograph interpretation and a detailed 1:10 000 scale ground survey. The survey involved extensive augering and the examination of many thousands of boreholes held by the BGS. These were used to generate a 3D fence diagram and calculate a block model for the York–Haxby area.





During the Devensian glaciation, the Vale of York was glaciated by the main onshore ice-sheet moving south-eastwards down the Vale and ploughing into a large proglacial lake (Lake Humber) that was impounded by North Sea Ice blocking drainage through the Humber Gap farther south-east, depositing laminated clays forming the Hemingbrough Glaciolacustrine Formation. The ice then overrode the lake deposits forming a terminal moraine at Escrick (EM, Figure 15). This is now confirmed as the last glacial maximum limit (LGM) within the Vale of York. The ice then decayed to form another moraine complex at York (YM), followed by further decay producing other moraines farther to the north-west (all moraines shown in green Figure 15). Long-lived drainage routes in the ice resulted in linear esker belts (in red) and the impounding of proglacial meltwater resulted in a complex array of glaciofluvial–glaciolacustrine sedimentation.

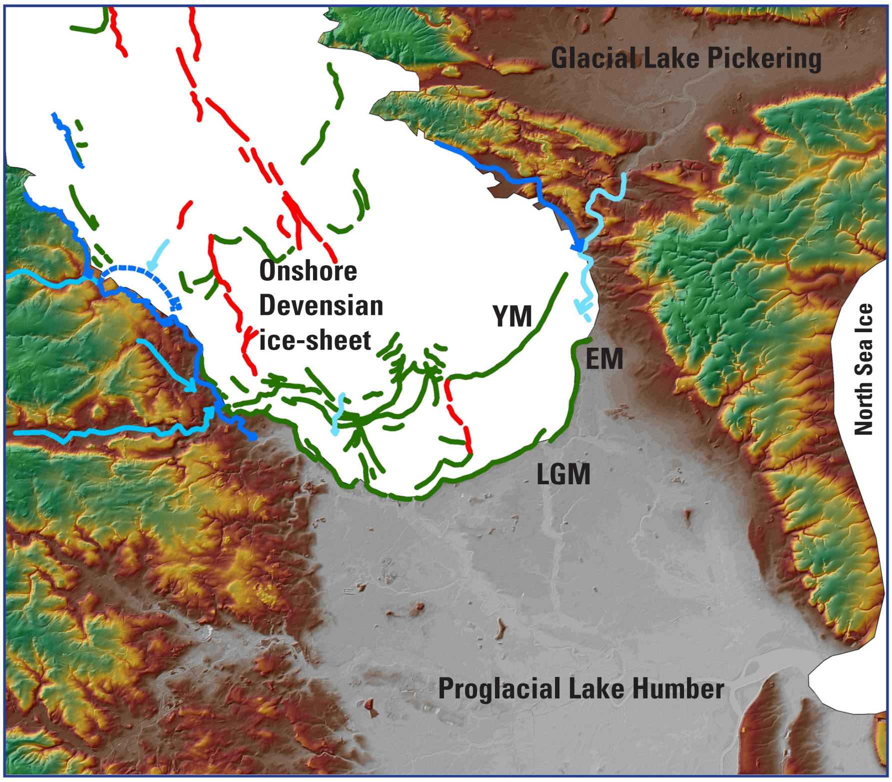
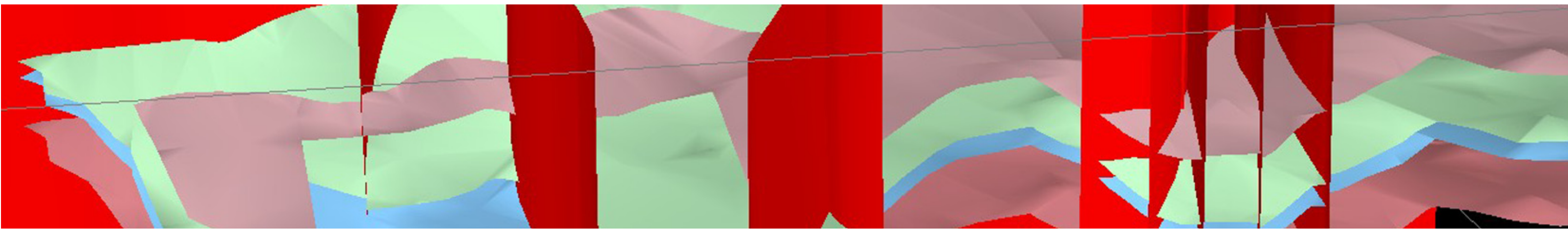


Figure 15 Reconstruction of the last glacial maximum in the Vale of York

[1] British Geological Survey, UK



New insights into the superficial geology of the Clyde Basin from NEXTmap and GSI3D models

Joanne Merritt[1], Diarmad Campbell[1], Katie Whitbread[1], Andrew Finlayson[1], Sue Loughlin[1], Sarah Arkley[1], Michael Browne[1], Brighid O'Dochartaigh[1], Malcolm Graham[1], Fiona Fordyce[1], David Entwisle[1], Alison Monaghan[1], Gaud Pouliquen[1], John Isaacs[2] and Martha Lovatt[3] (Contributors; Louise Ander[1], Andrew Hughes[1], Majdi Mansour[1], Dave Jones[1], Simon Price[1], Hugh Barron[1])

The Clyde Urban Super Project (CUSP) is an integrated BGS project that brings together scientific intitiatives under the Responsive Surveys Scotland and Urban Development teams. It addresses a wide range of environmental issues in the Clyde Valley, an area of national strategic importance. The area has been blighted by contamination and other environmental problems from its former mining and heavy industry, and so is Scotland's main target area for regeneration over the next 25 years, as well as being host to the 2014 Commonwealth Games. These have all been primary drivers for the recent research, data collection and 3D modelling that BGS has undertaken in this area. Initial work addressed the needs of the local authorities, and especially Glasgow City Council, who commissioned or co-funded some of the research and modelling. This work continues, and high quality geodata and 3D models are being produced for use by local authorities and urban planners. However, with shortages in local authority funds, and the greater emphasis on scientific output in the BGS, the project has adapted to focus more on integrating geological, geotechnical, hydrogeological, geochemical and geomorphological data, both onshore and offshore, to address a wider range of scientific problems in the greater Clyde Valley. The scientific approach has led the project away from 10 k sheet tile modelling of the particularly complex bedrock and superficial deposits towards modelling areas where difficult scientific questions need answering. By actively encouraging data and knowledge sharing and collaboration with local authorities and universities we are now becoming able to produce the fit-for-purpose quality 3D attributed geological models needed to answer difficult strategic, scientific, and increasingly trans-disciplinary questions.

Recent work in the Clyde Valley has addressed problems of past sea-level changes, flow patterns and limits of pre- and late-Devensian ice sheets, and the nature, distribution and origin of extremely deep and laterally continuous bedrock depressions in the area (Figure 16). In addition, development of a complete bedrock and superficial model is in progress, integration of hydrogeological data into GSI3D superficial models via Zoom grids has been tested successfully, potential contamination of shallow groundwater from surface sources has been assessed (the newly developed GRASP tool), and, for the first time, the linkage of offshore seismic data with onshore GSI3D models is being investigated. There are also plans to incorporate utilities and archaeological data into the models, and to integrate the GSI3D models with models of surface features, including building and other infrastructure. This has all been possible by the integrated use of ARC GIS, GSI3D, ZOOM, Landmark and GOCAD software. At the same time, the scope of the work is expanding as new trans-disciplinary relationships are being forged with univiersities to address issues such as sustainable urban drainage, flooding, groundwater contamination, and the potential impacts of extreme weather events and climate change on local communities and their sustainability.

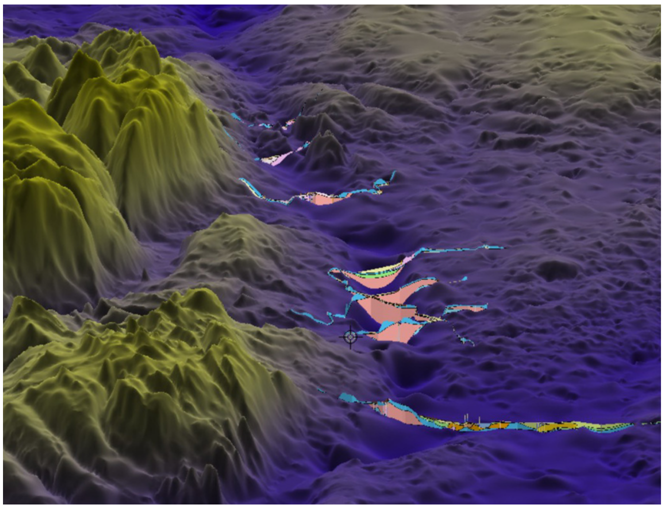
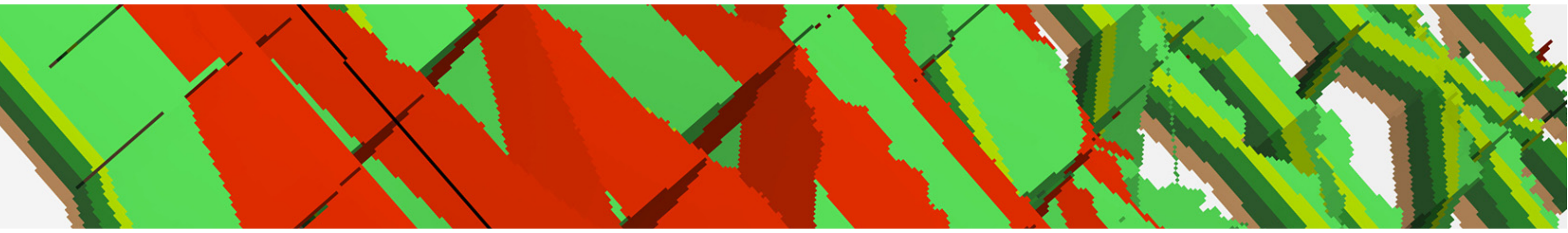


Figure 16 View to the east of selected geological cross-sections modelled across the Kelvin Valley, showing extensive glaciofluvial (mainly sand and gravel) sediments (pink) infilling a pre-late Devensian glaciation, bedrock depression, up to 100 m deep and extending 50 km across the Midland Valley of Scotland. The depression can be seen in the BGS rockhead model (coloured green for high and dark blue for low elevations).

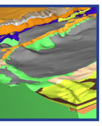
[1] British Geological Survey, UK, [2] Abertay University, UK, [3] Strathclyde University, UK

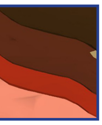


The development of chalk catchment ground models in southern England and northern France

Neill Hadlow[1], Ian Molyneux[1] , Alex Gallagher[2] and Christian Robelin[3]

Chalk catchments are geologically complex. Complexities relate to variation in bedrock geology, such as stratigraphy, structural geology, karst and weathering; superficial geology and geomorphology. The 3D visual ground models allow presentation and study of geological information, stratigraphical and non-stratigraphical, relevant to a particular problem whether environmental, engineering or hydrogeological. The visual ground models presented here were developed in conjunction with the FLOOD1 research project.





FLOOD1 was a tripartite research project funded by the European Regional Development Fund to investigate the role of groundwater in flooding events on Chalk catchments of the Interreg IIIA region. The FLOOD1 project partners comprised Bureau Recherche Geologique et Minières (BRGM), the British Geological Survey (BGS) and the University of Brighton. The FLOOD1 Interreg IIIA research catchments were the Patcham catchment, Brighton, England and the Hallue catchment, Somme, France.

As part of the FLOOD1 project a programme of geological field investigation was undertaken which involved mapping, analysis of borehole core and downhole geophysical surveying. The initial scope of this work was to contribute to current geological mapping in the research catchments and provide a series of geological cross-sections which would form the basis of conceptual models. In the UK the lithostratigraphical framework developed by Mortimore (1986) and Bristow et al. (1997), and outlined by Rawson et al. (2001), was utilised for field data collection. In France, field data was collected and interpreted using the UK lithostratigraphical framework but was combined with the existing French biostratigraphical framework, determined by Christian Monciardini, to develop a unique catchment lithostratigraphy.

GSI3D version 1.5.2, although originally designed for superficial geology, was used for construction of the cross-sections. The data and methods used to construct the cross-sections varied between the research catchments; in the Patcham catchment surface mapping was correlated with borehole logs whereas in the Hallue catchment surface mapping was correlated with quarry logs. Secondary 'filling' cross-sections were added between the primary cross-sections with the aid of guide bedrock surface grids. This allowed the development of full bedrock geological models. The GVS file (generalised vertical stack) for the Hallue catchment was configured to display the model in both the UK and French stratigraphical framework. Superficial deposits, due to a lack of suitably dense data, were modelled in a systematic way and the envelopes were enhanced with DAT files. Selected marl horizons from the New Pit and Lewes Nodular Chalk Formations were modelled as lenses. Non-stratigraphical information such as water tables and estimated rock head were also required to be modelled as lenses to allow them to be incorporated into the subsurface viewers.

The geological models were embedded into GSI3D subsurface viewers which facilitated dissemination of the models to the project partners. The GSI3D subsurface viewers allow construction of synthetic cross-sections in any orientation through the models and enable observe of spatial interactions between surfaces and units, for example the groundwater flooding water table, the weathered zone and a bedrock unit. As a result of this study on the geology of the Patcham and Hallue catchments, and the development of these ground models, new geological maps of the research catchments have been produced and understanding of the geology, and its interaction with the water table, has been enhanced.

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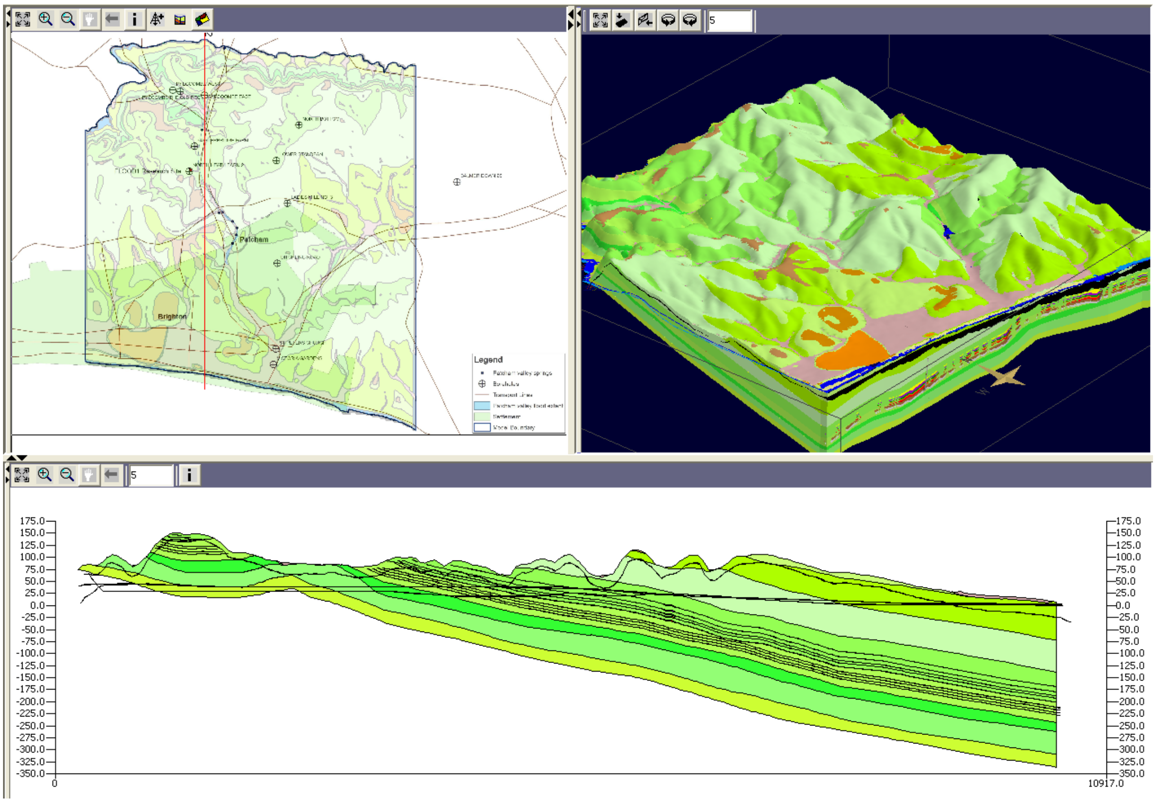


Figure 17 The Patcham 3D geological model in the subsurface viewer.

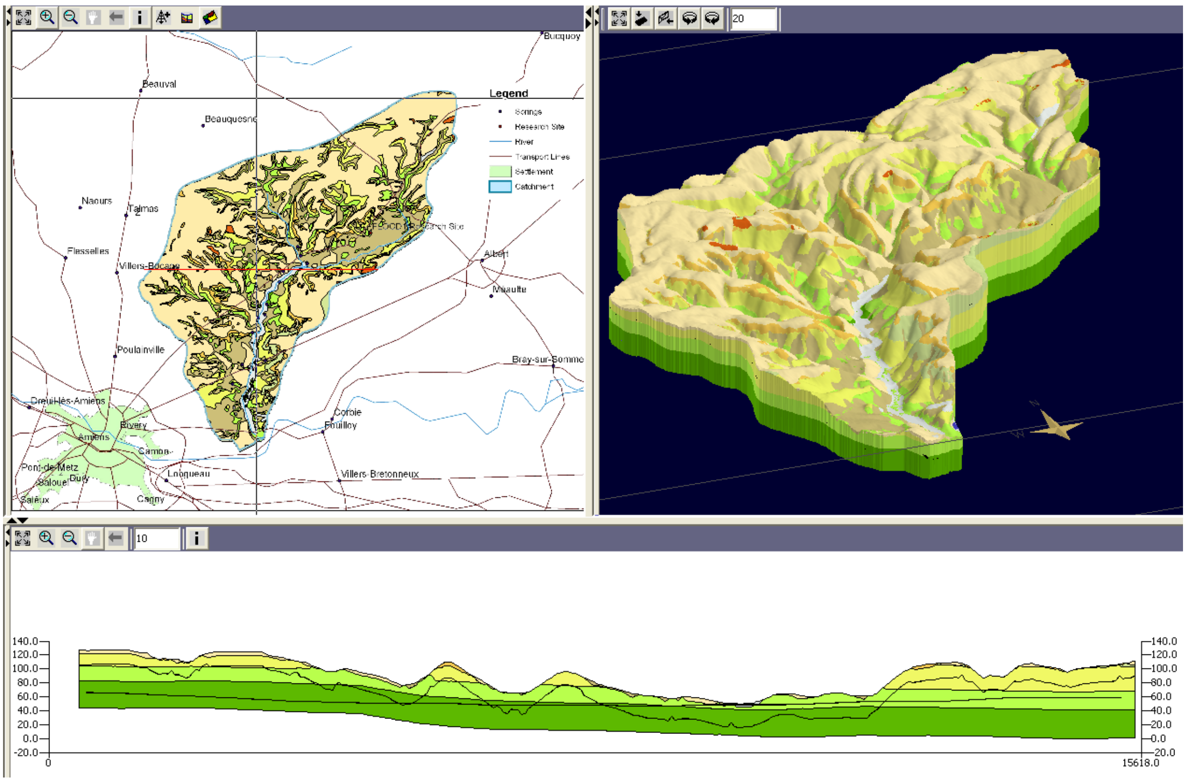
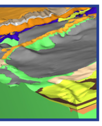


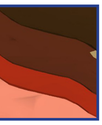
Figure 18 The Hallue 3D geological model in the subsurface viewer.

3D subsurface characterisation of the Netherlands: results from stochastic modelling

Jan Stafleu[1], Denise Maljers[1], Jan Gunnink[1], Armin Menkovic[1] and Freek Busschers[1]

The Geological Survey of the Netherlands aims at building a 3D geological model of the upper 30 m of the subsurface of the Netherlands in order to provide a sound basis for subsurface related questions on groundwater extraction and infrastructural issues. The Province of Zeeland (south-west Netherlands, covering an area of approximately 70 x 75 km) was chosen as the starting point for this model due to its excellent dataset of 23 000 stratigraphically interpreted wells.





The Zeeland model was constructed using the following procedure:

1. 2D bounding surfaces were constructed that allowed placing each 3D grid cell (100 x 100 x 0.5 m) within a correct lithostratigraphical context at formation and member level.

2. The lithological data from each well was transferred into a lithofacies code using newly developed, Python-based software. Examples of lithofacies zones include tidal channels, tidal flats and coastal dune sands.

3. The combination of the lithostratigraphical model and the lithofacies zonations, allowed us to perform a final interpolation procedure in which a 3D, 50 million cell lithofacies model was constructed.

The procedure described above resulted in a 3D regional-scale facies model of Tertiary, Quaternary and Holocene strata. As an example, the 2D surface in Figure 19 represents the base of the Holocene Walcheren Member. Cross-sections superimposed on the surface reveal the 3D facies distribution within this member. Facies include tidal flats (green), tidal channels (yellow) and shell crags (blue). A detail of Figure 19 is shown in Figure 20a.

The use of stochastic techniques allowed us to compute probabilities for both lithofacies and stratigraphy for each grid cell, providing a measure of model uncertainty. Figure 20b shows the probability that a cell belongs to the tidal channel facies. Red indicates a high probability, lighter tones indicate a low probability. Analogously, the probability that a cell is part of the Walcheren Member is shown in Figure 20c.

The Zeeland model provides important new insights on spatial connectivity of sediment units like for example Early Pleistocene floodplain clay layers and patterns of sandy Holocene tidal channel systems. Our results represent a major step forward towards a cell based, 3D model of the Netherlands that should eventually replace the existing 2D models.

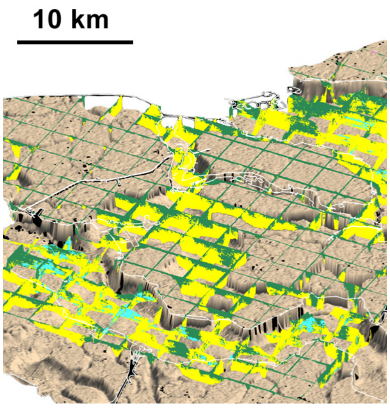


Figure 19 The base of the Holocene Walcheren Member. Cross-sections superimposed on the surface reveal the 3D facies distribution including tidal flats (green), tidal channels (yellow) and shell crags (blue)

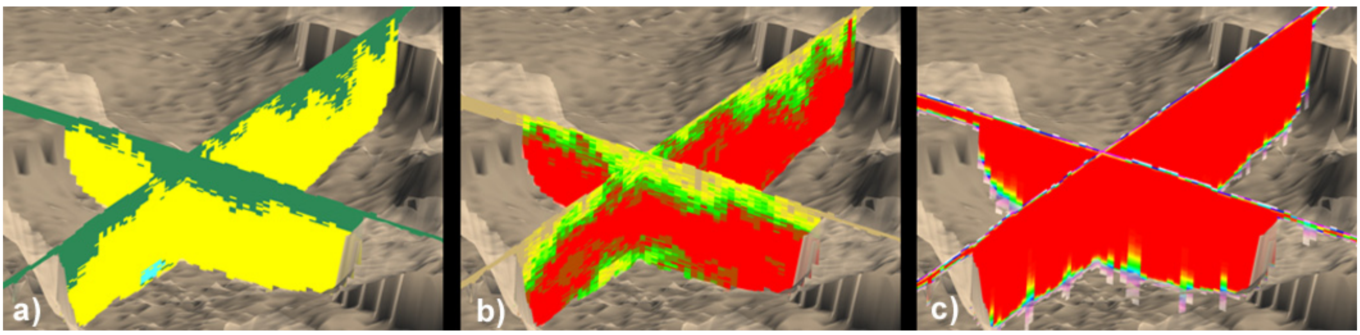


Figure 20 Detailed view of part of the model shown above in Figure 19, for full explanation see text.

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The integration of 3D geophysical and geological modelling techniques for investigating buried sand and gravel deposits: an example from the Quaternary Bytham River Terrace of eastern England

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We describe a study in which 3D electrical resistivity tomography (ERT) and 3D geological modelling, using GSI3D, were applied to the evaluation of a complex sand and gravel deposit. By combining these techniques we were able to use high-resolution 3D ERT images to refine a 3D geological model of the site, which was generated in the first instance using only borehole data. We illustrate our approach using a case study from a quarry extension site at Ingham, Suffolk. The site comprises heterogeneous river terrace sand and gravel deposits of variable thickness, which are partially overlain by glacial till; the bedrock consists of chalk, the upper surface of which displays significant topographical variations. The Ingham 3D ERT survey provided a high quality ground/mineral model that revealed significant geological structures, such as channel features, which were not apparent from the borehole data alone. In retrospect, it is clear that a 3D ERT survey in the initial stages of site investigation could have reduced the number of boreholes needed for the resource assessment, and would have allowed boreholes to be targeted more effectively. The refined 3D geological model, which incorporated smaller scale features identified from the ERT data, provided a high-resolution 3D representation of the deposit from which overburden and mineral volumes could be directly determined. Furthermore, we have illustrated how surfaces such as 'bedrock' and 'base of overburden' can be exported from GSI3D in a format that can be directly imported into industry-standard terrain modelling packages such as LSS.

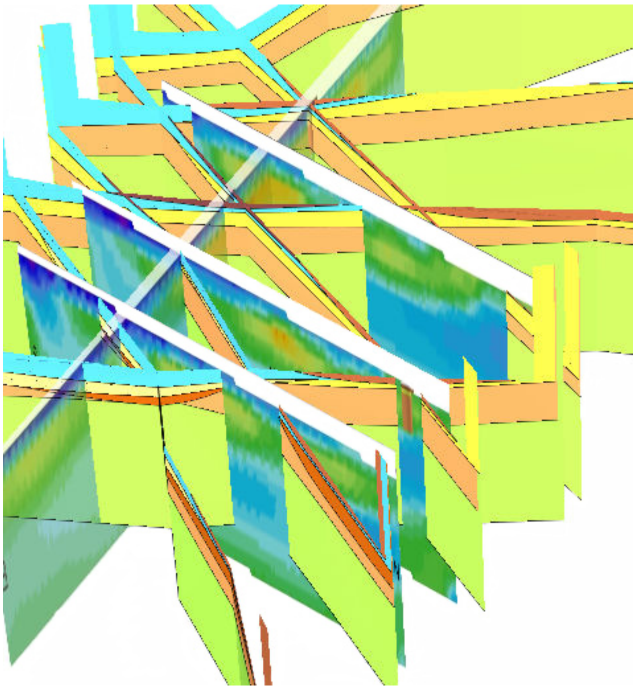


Figure 21 Geophysical sections incorporated into GSI3D workspace.

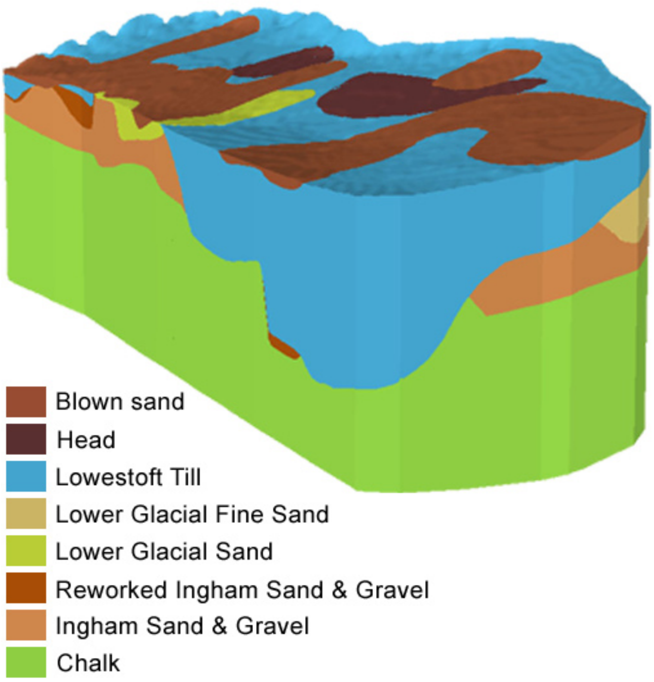
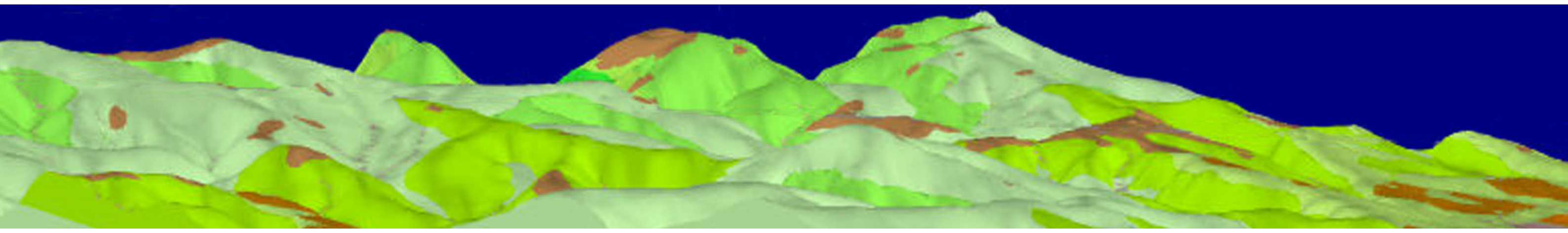


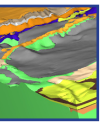
Figure 22 Block model.

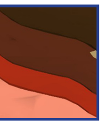
[1] British Geological Survey, UK



ZOOM in to GSI3D: using 3D geological models to better parameterise groundwater models

Andrew Hughes[1], Malcolm Graham[1], Chris Jackson[1], Majdi Mansour[1] and Thalia Vounaki[1]





The BGS, in collaboration with the University of Birmingham and with the support of the Environment Agency of England and Wales has been developing a suite of object-oriented (OO) groundwater models. The suite includes a groundwater flow model, ZOOMQ3D (Jackson et al., 2004), an advective particle tracking model, ZOOPT (e.g. Stuart et al., 2006) and a distributed recharge model, ZOODRM (e.g. Hughes et al., 2008). The aim of using OO techniques was originally to incorporate grid refinement to attempt to solve the scale problem in modelling groundwater systems (e.g. Spink et al., 2006). As experience grew in using OO techniques, it became apparent that other benefits could be accrued. These include improved representation of geological volumes. To better understand the implications of doing this, it was decided to link ZOOMQ3D to GSI3D. This abstract describes the use of GSI3D models in enhancing ZOOMQ3D groundwater flow models.

Examples of GSI3D-ZOOM linkages

INSIGHT were commissioned by BGS to build an export function into GSI3D to facilitate its linkage with the ZOOMQ3D model. The GSI3D model uses the locations of the finite-difference nodes in a ZOOMQ3D model to calculate the elevation and hydraulic conductivity of the layers in the groundwater flow model. Two columns are added to GSI3D's 'gvs' file which is used to parameterise the geological model: one to define which geological volumes are translated into ZOOMQ3D layers and one to define the associated hydraulic conductivity values. GSI3D exports two files that contain the elevation of each ZOOMQ3D layer (top and bottom) and the hydraulic conductivity values. ZETUP, the pre-processor for ZOOMQ3D, then converts these files into the correct format for input into the flow model ZOOMQ3D.

The GSI3D-ZOOMQ3D linkage was first successfully tested on a relatively simple geological model developed for the BGS research site at Shelford, near Nottingham. This showed that the linkage worked and that a refined geological model was required where any problems, such as layer bottoms being above the top of the layer, were resolved. Recent examples of the use of GSI3D models to enhance ZOOMQ3D models

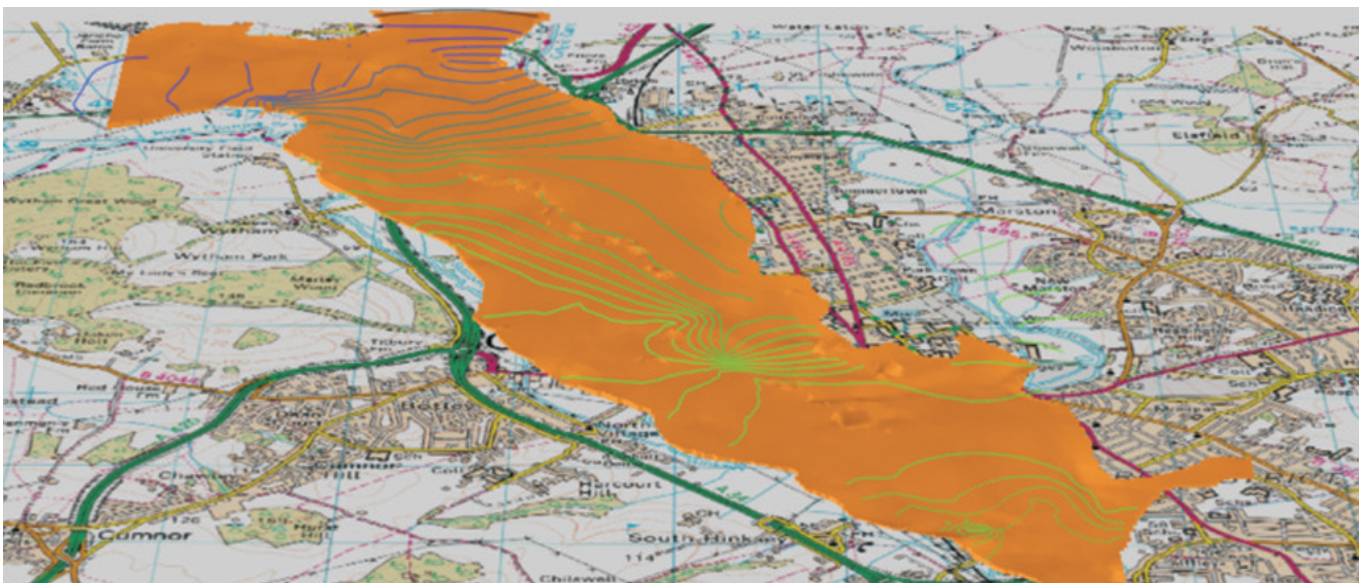
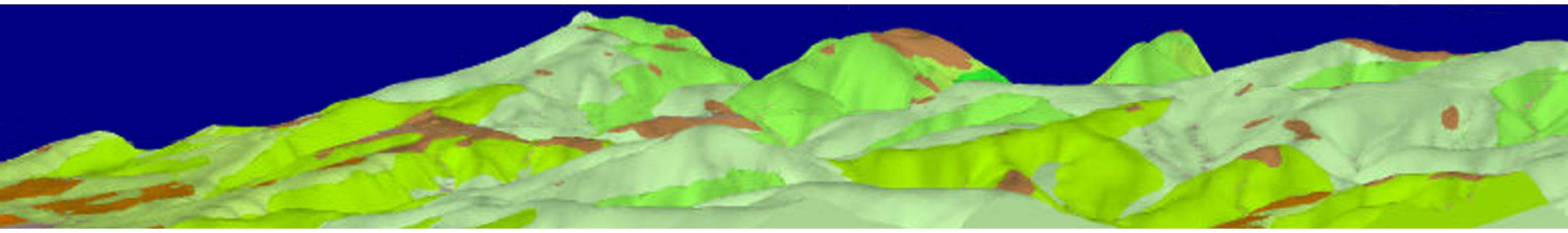


Figure 23 The Oxford groundwater flooding model.

[1] British Geological Survey, UK



include: The Goring Gap project (Jackson et al., 2007), where a GSI3D model of the valley gravels was used to define the base of a layer along the Thames valley. The Oxford Flooding project (Macdonald et al., 2007), where a geological model of the gravels underlying Oxford was constructed and used to provide an improved layer geometry for ZOOMQ3D (see Figure 1). The Clydeside project (Merrit et al., 2007), where a GSI3D model of a 75 km^2 area has been used to develop a ZOOMQ3D model to help the understanding of the hydrogeology of the superficial deposits underlying Glasgow.

Lessons learnt

Before linking ZOOMQ3D to GSI3D, geological complexity has to be considered. Layered models such as ZOOMQ3D (and MODFLOW) are not designed to cope with these situations and problems with the dewatering of model nodes can result. Therefore, the geology has to be simplified. Consideration must also be given to the development of the geological model with respect to the accuracy of the volumes and the 'finishing' of the geological model so that layer bottoms do not have a higher elevation than the top of layer. The flow model identifies these problems that are difficult to detect when using GSI3D just to visualise geology. Ideally, the geological model must enclose the flow model so that the model layer geometry can be defined using a consistent approach. Further, the use of grid refinement within ZOOMQ3D and the relationship between the geological models and the scale of the groundwater model is an important consideration. Detailed geological modelling may take place in a smaller area than the groundwater model covers. The groundwater boundaries will not necessarily be coincident with the area of the detailed geological model and there is a need for 'nested' geological models with different scales of complexity.

The way forward

The next step is the increased use of GSI3D models in groundwater modelling investigations to make it routine to use a geological model to define the geometry of a groundwater flow model. Groundwater model results will also be visualised in GSI3D. There is a need to investigate the issues of scale of development of geological models and grid refinement within ZOOMQ3D. The linkage between GSI3D and ZOOMQ3D has highlighted the limitations of layered groundwater flow models in representing geology properly. The BGS is now involved in the development of a groundwater flow model that represents geological and hydrogeological complexity more accurately using finite-volume techniques.

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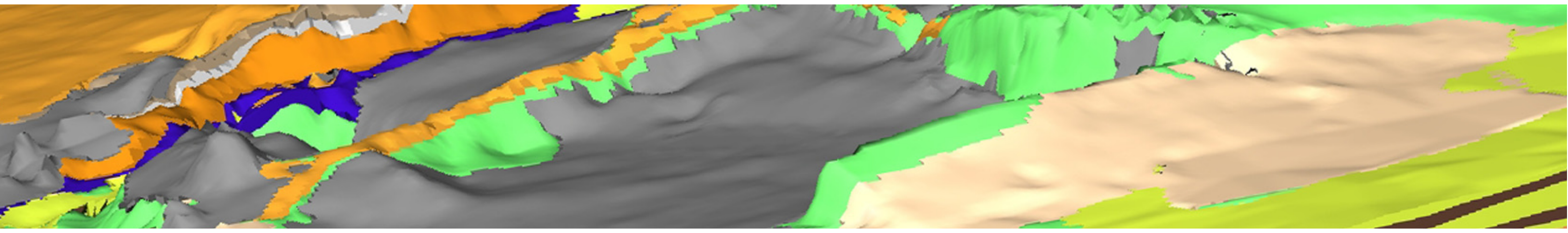

The vision goes on

Hans-Georg Sobisch[1]

Research and development of GSI3D over the past 10 years has enabled geological surveys to produce systematic 3D geological models as part of their standard survey process. Initially this was solved for superficial and unfaulted bedrock environments, but now we have expanded the GSI3D methodology to deal with almost the whole geological inventory. The primary driver behind these developments was to create the 3D geological map as the successor to the 2D digital map. This has been achieved with the deployment of the subsurface viewer in 2005.

The availability of large volumes of systematic and site specific 3D models combined with new ways of distributing and visualising subsurface information has led to increased demand of geological data as well as information on their properties. As you would expect, this demand is greatest from customers involved in applied studies, such as groundwater management, urban planning and geotechnical investigations.

These developments inevitably mean that 3D subsurface information needs to be visualised and managed in common software platforms, analogous to 2D geodata in a GIS. This means that we need a general solution for subsurface information containing geological framework, infrastructure, properties etc. The vision therefore is to build a 3/4D GIS to enable an optimal use of subsurface information and associated processes for the benefit of the environment and society as a whole.

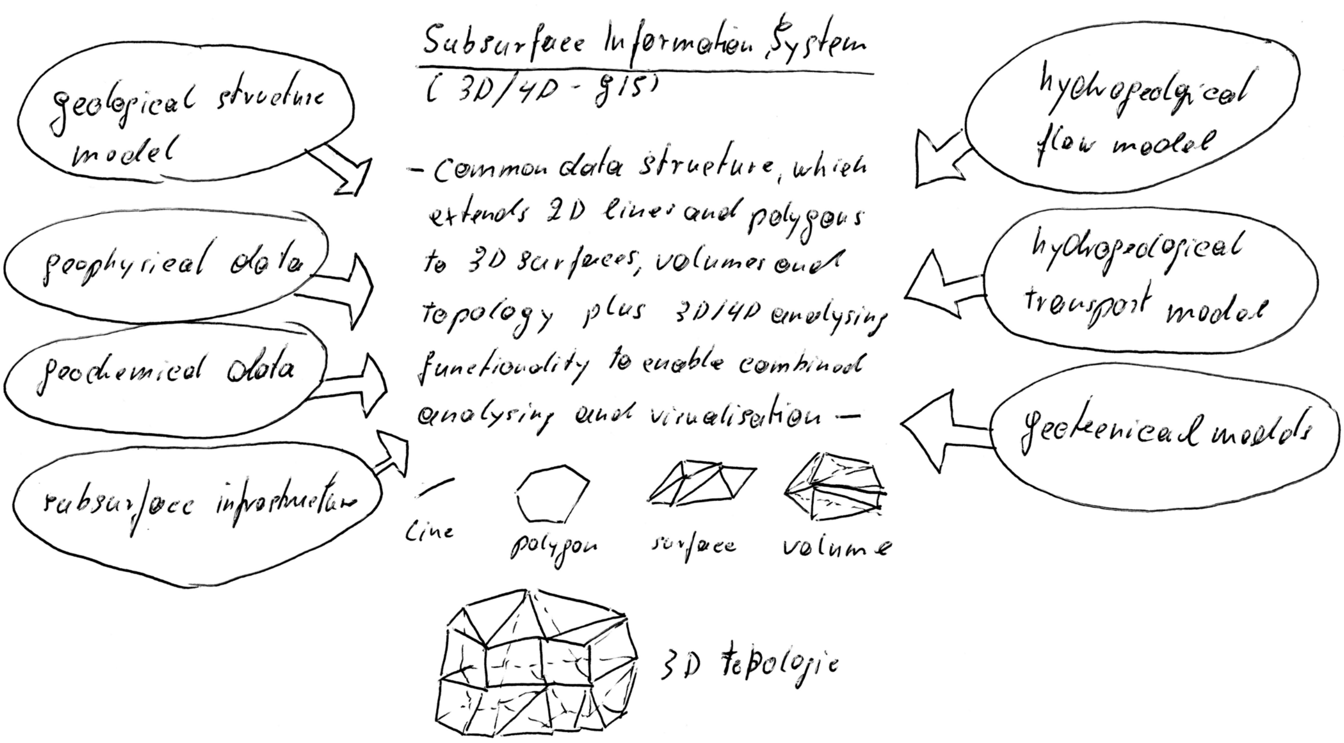

Figure 24 Napkin sketch outlining the vision of a Subsurface Information System.

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