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EDITOR'S INTRODUCTION

CASE STUDY 21-1: THE USE OF 3-D MODELS TO MANAGE THE GROUNDWATER RESOURCES OF THE LOWER GREENSAND CONFINED AQUIFER, HERTFORDSHIRE AND NORTH LONDON, ENGLAND

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CASE STUDY 21-2: REGIONAL 3-D MODELS OF BREMEN, GERMANY: MANAGEMENT TOOLS FOR RESOURCE ADMINISTRATION

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CHAPTER 21: APPLICATION THEME 4: REGULATORY SUPPORT

EDITOR'S INTRODUCTION

The support of regulation and management of subsurface uses is a new but rapidly growing use of 3-D geological models. To date, the primary regulatory use of 3-D geological models has been to support groundwater resource management (Chapters 6 and 19). More recently, 3-D models have been used for geothermal resource assessment and management; Chapter 20 provides three geothermal case studies and summarizes additional recent developments. Regulation and management issues also influence the use of models for geohazard mitigation (Chapter 22) and infrastructure (Chapter 23). Chapters 3 and 16 explore in some detail the various interactions between geological information (and models) and the urban planning issues surrounding societal desires for environmental protection, resilience, and sustainability. Chapter 14 provides additional information on the interactions between 3-D geological models and 4-D process models

Regulation of the subsurface is evolving in many countries, and the use of appropriate technologies to define and assess alternative solutions to societal goals is increasingly becoming recognized as an inherent part of urban planning and resource management processes. Chapter 18 has three case studies of 3-D models for urban planning, including Glasgow where a long-term collaboration between the British Geological Survey and Glasgow City Council has resulted in establishment of a contractual requirement to deposit and share data in a knowledge exchange network "Accessing Subsurface Knowledge (ASK)", which provides links to a broad range of stakeholders who either use and/or generate subsurface data within any stage of the city development process (Bonsor, 2017).The use of 3-D models is particularly important in the very rapidly growing cities of south-east Asia (see Case Study 18-3, which describes a model for Dhaka, Bangladesh).

The first case study describes how a 3-D geological model provided by the British Geological Survey assists Environment Agency of England and Wales (EA) in assessing alternative sources of water supplies in the Hertfordshire and North London (HNL) area where the current groundwater withdrawals are adversely affecting the baseflow of several streams originating in the Chalk Group aquifer. The model supports the EA with appropriate responses to demands by public water suppliers and large industrial users for new licenses to abstract water from the Lower Greensand Group confined aquifer as an alternative water source to meet their business needs.

The second case study describes the regulatory uses of 3-D geological models by the Federal State of Bremen, the smallest of the three German city states, which consists of the two cities Bremen and Bremerhaven. Located in northwestern Germany, this densely populated industrial area experiences a wide range of subsurface problems related to building construction, transportation and water supply infrastructure improvements, and utilization of geothermal energy sources. These activities are influenced by contaminated soils and waste deposits at many locations, the risk of flooding due to storm events and, over a longer term, a rising sea level and associated ground water salinization. In response to these concerns, the Geological Survey for Bremen has developed a 3-D geological model of the subsurface Quaternary units and upper Tertiary units. This model and a derived steady-state groundwater flow model support government administrative actions, planning for construction projects, and issues related to groundwater use and geothermal development. Products derived from these models are provided to public and private sectors, partially through a web-service.

CASE STUDY 21-1: THE USE OF 3-D MODELS TO MANAGE THE GROUNDWATER RESOURCES OF THE LOWER GREENSAND CONFINED AQUIFER, HERTFORDSHIRE AND NORTH LONDON, ENGLAND

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1. INTRODUCTION

The Hertfordshire and North London (‘HNL’) area of England is currently water-stressed; provision of adequate water supplies while balancing ecologic and economic goals is challenging. The Chalk Group aquifer is the major groundwater source; current groundwater withdrawals are adversely affecting the baseflow of several streams originating in areas underlain by chalk. The Environment Agency, in its role as a public regulatory body, is implementing a comprehensive program of investigations and actions to return the HNL area to a sustainable abstraction regime. Public water suppliers and large industrial users are being compelled to look for alternative water sources to meet their business needs. The Lower Greensand Group confined aquifer, despite its higher development costs and lower yields, is becoming an increasingly important alternative source.

The Environment Agency must consider the concerns and interests of all user-groups when arriving at licensing decisions. Several water suppliers have recently requested the Environment Agency provide new licenses to abstract water from the Lower Greensand Group confined aquifer. Currently, the Environment Agency has no formal strategy for managing abstractions from the Lower Greensand Group confined aquifer; each application decision is on a case-by-case basis. Existing hydrogeological knowledge of the HNL area is relatively limited. Better knowledge would help achieve the Environment Agency goal of enhanced, sustainable development of the Lower Greensand Group confined aquifer. The Environment Agency commissioned the British Geological Survey ('BGS') to construct a 3-D geological and hydrogeological model of the Lower Greensand Group aquifer (Figure 21-1).

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Figure 21-1 NEAR HERE

Fig. 21-1. Location of the model area, including the bedrock geology, boreholes used and principal cross-section location [Contains Ordnance Survey data © Crown Copyright and database rights 2017]

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2. GEOLOGICAL SETTING

Bedrock in the HNL study area consists of a suite of Mesozoic to Cenozoic marine sedimentary rocks (Table 21-1) that dip gently to the southeast (Hopson *et al.,* 1996; 2008). The Lower Greensand Group aquifer within the model area consists of the Woburn Sands Formation, a Cretaceous shallow marine sandstone; it is supplemented by several minor sand formations (Hopson *et al.,* 2008). These sands are confined where relatively impermeable formations above the Lower Greensand Group form aquicludes. A varied sequence of shallow Quaternary deposits (Table 21-2) overlies a NE-SW trending outcrop zone of the Lower Greensand Group. This creates an important recharge zone for the Lower Greensand Group. A buried glacial channel, termed the 'Hitchin Buried Valley' extends in a southerly direction in the area around Hitchin (Hopson *et al.,* 1996). Filled with over 100 m of glacial deposits, it extends into the underlying bedrock formations, creating an important hydrogeological feature.

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TABLES 21-1 and 21-2 NEAR HERE

TABLE 21-1. Simplified bedrock stratigraphy of the Lower Greensand Group model area with hydrogeological properties (Youngest first).

TABLE 21-2. Stratigraphic sequence and hydrogeological characteristics of surficial deposits in the Lower Greensand Group outcrop area; they influence aquifer recharge rates.

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3. DEVELOPING THE 3-D LOWER GREENSAND GROUP SUBSURFACE MODEL

The 3-D geological model of the Lower Greensand Group aquifer (Figure 21-2) was developed by following the borehole and cross section approach for model construction discussed in Chapter 10. The GSI3-D software currently used by the BGS (Kessler *et al.,* 2009) developed the 3-D model. However, data preparation and model visualization utilized additional software, including Microsoft® Access, Esri® ArcGIS, and GroundHog® desktop (Wood *et al.,* 2015). The model was constructed with six bedrock units and sixteen Quaternary surficial units (Table 21-3). Model units represent critical hydrogeological characteristics of the geologic model area; permeable bedrock units with no hydraulic connectivity to the Lower Greensand Group confined aquifer are undifferentiated in the model. The model includes Quaternary surficial deposits where they influence the hydrogeology of the Lower Greensand Group recharge zone.

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Figure 21-2 NEAR HERE

Fig. 21-2. A) Location of the geological cross-sections; B) 3-D fence diagram of the model cross-sections; C) Example of three cross-sections, A and B being 'principal' cross-sections, and C being an example of a 'helper' cross-section

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Table 21-3 NEAR HERE

TABLE 21-3. Generalized Vertical Section (GVS) for use in the GSI3-D modeling process

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3.1 Data Selection and Preparation

Lithological and geophysical borehole records held in the BGS database are the primary source of subsurface information. Thirty-four geophysical logs helped define geological unit boundaries. Lithologic borehole logs were of variable quality; many predated the 1950s and so contained obsolete terms or inaccurate measurements. Moreover, they were not optimally placed; many are shallow borings. There is a paucity of information in the southeastern model area. Several areas have clusters of shallow boreholes. The model is based on 203 representative boreholes selected from 20,546 boreholes within the model area. Key stratigraphic surfaces were defined using GroundHog® desktop GSIS software (Wood *et al.,* 2015) materially assisting the definition of key stratigraphic surfaces. The Ordnance Survey Terrain 50 Digital Terrain Model (Ordnance Survey Limited, 2017) defined the topography; DigMap-50, a digital BGS geological map at 1:50,000 scale (British Geological Survey, 2017a) defined the spatial extents of geological units. Both datasets were converted to 50 m grids for use in the model. GSI3-D controlled the model stratigraphic relationships using a digital Generalized Vertical Section (Table 21-3).

3.2 Model Construction

The model extends from the surface to a depth of 500 m below Ordnance Datum and covers an area of 2,349 km2 (907 square miles). The model was constrained by 20 interpreted geological sections; 10 sections were oriented NW-SE and 10 sections NE-SW (Figure 21-2). This orientation of the sections roughly follows the regional dip and strike. Five geological cross-sections from the nationwide geological fence diagram UK3-D (British Geological Survey, 2017b) were used to guide model development. The model initially was formed as a 3-D fence diagram (Figure 21-2B). Outcrop locations defined by

DiGMapGB-50 (British Geological Survey, 2017a), supplemented by digitized sub-crop limits, and defined the lateral extents of each geological unit. Base surfaces of alluvium and head deposits were defined by assuming a thickness for each unit within its extent. This procedure accurately represented these units while avoiding additional cross sections.

An iterative process was employed to convert the network of cross sections into a completed 3-D model (Figure 21-3). Adjustments were required in areas that did not conform to expected geological conditions. In these locations, new 'helper' cross-sections were developed to constrain geological units and produce a satisfactory model.

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Figure 21-3 NEAR HERE

Fig. 21-3. A) The calculated geological model; B) Close up of the 3-D calculated surficial geology of the Lower Greensand Group outcrop/recharge zone

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4. MODEL PRODUCTS

The completed 3-D model was used to produce several digital products for the Environment Agency and the groundwater user community. Initial outputs included some 2-D derived products that could be used by standard GIS software, including:

- ASCII grids of the tops, bases and thicknesses of the geological units;
- ESRI shapefiles of the lateral extents ('geological envelopes') of each geological unit;
- Procedures defined by Lelliott *et al.* (2006) produced a "hydro-domain map" which provides users with a 2-D characterization of the hydrogeological properties of the intercalated surficial deposits in the recharge area (Figure 21-4).

The completed 3-D model was provided to the Environment Agency accompanied by the free BGS 'Lithoframe viewer' which allows viewing, investigation, and query of the 3-D geological model with a simple GIS-type interface (Waters *et al.,* 2015).

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Figure 21-4 NEAR HERE

Fig. 21-4. A) "Hydro-domain map" of the Lower Greensand Group outcrop zone; B) "Hydro-domain" characterization.

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Further output products were specifically related to the hydrogeology. Attributes defining the aquifer designation, the flow mechanism, and the productivity characteristics of each geologic unit (shown in Tables 21-1, 21-2 and 21-3) allowed the model and sliced virtual cross sections to be colored to define important geohydrological considerations (Figure 21-5). A full scientific report (Cripps *et al.,*

2017) contains further hydrogeological information and provides a succinct summary of current hydrogeological knowledge for this area.

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Figures 21-5 NEAR HERE

Fig. 21-5. A) Location map identifying example cross-section outlined below; B) Example geological cross-section showing: Geology (top); Aquifer Designation (middle); and Flow Mechanism, Productivity (bottom).

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5. APPLICATIONS OF THE 3-D MODEL AT THE ENVIRONMENT AGENCY

The Lower Greensand Group model provides a summary of the state of current geological and hydrogeological knowledge of the Lower Greensand Group in the model area. Water level data from the Environment Agency Cam-Bedford-Ouse (CBO) MODFLOW numerical groundwater model (ENTEC UK Ltd., 2007), was added to the GSI3-D geological model. This provided a crucial link in the decision-making process. It allowed the water table or potentiometic surface for each aquifer to be computed and displayed, providing for better management of the confined Lower Greensand Group aquifer as a water resource.

The Environment Agency is now embracing the use of 3-D models for improved decision-making at catchment and regional scales. The 3-D models are being used internally to educate staff and enhance their understanding of subsurface geology implications. The Environment Agency uses 3-D models to communicate with stakeholders to explain complex geological issues in a format readily understood by non-experts.

In addition to the LGS aquifer mode, a simplified 3-D geology model of the Chalk Group aquifer in the HNL area was developed by the Environment Agency as an additional tool to improve stakeholder understanding of existing numerical groundwater models (Figure 21-6). The 3-D chalk model has successfully communicated complex issues of groundwater and surface water interactions to various non-specialist audiences interested in maintaining sustainable balances among ecologic and economic goals. The chalk model permits the 3-D visualization of the chalk geology of the HNL area while simultaneously illustrating three static groundwater level scenarios: long term average, 2001 flood level, and 2006 drought level. These scenarios allow individuals to relate their experiences of past extreme climatic events with potential groundwater resource use and management practices. The model has also been used to explain how groundwater resources can be protected from human activities and influences.

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Figure 21-6 NEAR HERE

Fig. 21-6. A) Calculated model of the River Chess catchment area, showing bedrock Cretaceous strata (different green colors) and Quaternary Surficial deposits (all other colors). (Farrant *et al.*, 2016). B) Location map of the Chess catchment model (blue) within the Lower Greensand Group (LGS) model area (red).

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In the upper reaches of the River Chess catchment, groundwater abstractions for public water supplies are apparently contributing to low river flows. To support hydrogeological investigation of this situation, the Environment Agency, in conjunction with both Thames Water and Affinity Water, commissioned the BGS to build a 3-D geological model (Farrant *et al.,* 2016). The model produced an improved understanding of the stratigraphic variations in the chalk, its spatial variability in the catchment, and how this influences aquifer response to abstraction. The model has allowed refinement of the Southwest Chilterns groundwater model over the River Chess catchment and improved model calibration in this area.

CASE STUDY 21-2: REGIONAL 3-D MODELS OF BREMEN, GERMANY: MANAGEMENT TOOLS FOR RESOURCE ADMINISTRATION

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1. INTRODUCTION

The Federal State of Bremen is the smallest of the three German city states. Located in northwestern Germany, it consists of the two cities Bremen and Bremerhaven. The city of Bremen is located along the Weser River, about 60 km inland from the port city of Bremerhaven, located at the mouth of the Weser River. This densely populated industrial area experiences a wide range of subsurface problems related to building construction, transportation and water supply infrastructure improvements, and utilization of geothermal energy sources. These activities are influenced by contaminated soils and waste deposits at many locations, the risk of flooding due to storm events and, longer term, a rising sea level and associated ground water salinization.

In response to these concerns, the Geological Survey for Bremen (Geologischer Dienst für Bremen – GDfB) was commissioned to develop a 3-D geological framework model of the subsurface Quaternary units complemented by upper Tertiary units for the Federal State of Bremen. The model was constructed in two parts (Figure 21-7). The 3-D model for the city of Bremen was completed in 2011 containing five principal stratigraphic units; the 3-D model for Bremerhaven was completed in 2014 containing six principal stratigraphic units.

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Figure 21-7 NEAR HERE

Fig. 21-7. 3-D geological framework model of Bremen and Bremerhaven. Units from oldest to youngest (bottom to top): 5, 6 fluviatile and marine Tertiary sediments; 4 Elsterian glacial deposits; 3 Lauenburger glacio-lacustrine deposits; 2 Weichselian/Saalian glacial deposits; 1 Anthropogene/ Holocene deposits. Units 5 and 6 are combined for the Bremen model. (Seiter & Panteleit, 2016)

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The 3-D geological framework model and a derived steady-state groundwater flow model support government administrative actions, planning for construction projects, and issues related to groundwater use and geothermal development. Products derived from these models are provided to public and private sectors, partially through a web-service.

2. GEOLOGICAL SETTING

Bremen is located in the northern German lowlands; specifically, on the marshy lowlands of the Aller-Weser valley. The 3-D geological models are restricted to the Quaternary glacial and post-glacial Holocene deposits and complemented by upper tertiary units. The tertiary units are derived from the Geotectonical Atlas (GTA) issued by the LBEG (Landesamt für Bergbau, Energie und Geologie, Federal Sate of lower Saxony). Thus, the models contain four basic stratigraphic quaternary units and two (Bremerhaven), respectively one (Bremen) tertiary unit. (Table 21-4) which are from top to bottom : 1) Anthropogene/ Holocene Unit, 2) Weichselian/Saalian glacial deposits, 3) glacio-lacustrine Lauenburger unit, 4) Elsterian glacial deposits, 5) middle Miocene to Pliocene fluviatile and marine deposits and 6) lower Miocene marine deposits, which forms the lower boundary of the models. Glacial melt-water eroded these Tertiary deposits, forming buried valleys, up to 360 m below sea level in Bremen and 244 m below sea level for Bremerhaven, that were subsequently filled with sand, clay, and tills from three glacial cycles. These buried valleys are important groundwater sources which are partially protected from contamination from near-surface activities by the overlying predominantly clayey Holocene deposits.

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Table 21-4 NEAR HERE

TABLE 21-4. Simplified Quaternary and upper Tertiary stratigraphy of Bremen.

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The near-surface anthropogenic deposits include sands, which have been transported for building construction, road building, or filling of abandoned harbor basins with a maximum high above sea level of 40 in Bremen and 26 m in Bremerhaven. Debris layers from bombed buildings are ubiquitous. Waste deposits exist in some landfills and at a surface waste disposal site. The natural Holocene deposits include peat and organic clays in combination with fluvial and dune sands. The underlying Weichselian and Saalian glacial deposits contain gravel layers resulting from glacial valley drainage systems; the bulk of these deposits consist of sand interfingered with lenses of till. The Elsterian glacial deposits were modelled as two units: The Lauenburger unit consisting of fine glacio-lacustrine deposits, and an underlying unit composed of coarser glacial deposits, mostly sands and occasional interfingered till deposits.

3. DEVELOPMENT OF 3-D SUBSURFACE MODELS

Over the past 150 years, various construction and resource activities in Bremen have resulted in about 95,000boring records being archived by the GDfB. These boreholes range in depth from building inspections of a few meters to deep gas exploration wells. These borehole records were digitally coded, interpreted, and stored to form a GDfB borehole database. In addition to borehole locations and lithologic descriptions, many records include information on the screening depth of observation wells, geophysical parameters (gamma ray or resistance logs), groundwater chemistry data, measured water levels, and groundwater extraction rates (for production wells).

3.1 Geological Framework Model

Construction of the 3-D geological framework model was performed using the GOCAD 3-D modeling software by Paradigm. Data preparation and interpretation a GIS and GeODin (Fugro Consult GmBH) software was used to manage and interpret the information held in the GDfB borehole database. The extracted information was imported into GOCAD.

The 3-D geological framework model was designed to support the development of a discrete-element steady-state groundwater flow model. This method of groundwater flow simulation required layers to extend continuously across the entire model domain. Thus, the model contains a base layer (base Miocene) and six continuous hydrostratigraphic units corresponding the four Quaternary units and two tertiary units defined in Table 21-4.

Once the horizons defining these six hydrostratigraphic units were spatially located in the 3-D geological framework model, it was discretized into a regular 100 x 100 m grid (S-Grid in GOCAD). To allow for further evaluation, each hydrostratigraphic unit was divided vertically into a number of layers defined according to the thickness of the unit and its heterogeneity (Table 21-5). Thus, the vertical resolution of the model varies with the thickness of each stratigraphic layer and is not constant throughout the model (Figure 21-8).

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Table 21-5 NEAR HERE
TABLE 21-5. Descriptions and characteristics of 3-D model horizons and component units.
(Modified from Panteleit *et al.*, 2013)
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Figure 21-8 NEAR HERE
Fig. 21-8. Modified example of GOCAD S-Grid. (Seiter & Panteleit, 2016)
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In preparation for the groundwater flow modeling, the 3-D grid model was "parameterized" – the lithologic character of each cell was assigned appropriate parameter values. Interfingering lenses found within the units can now be identified by the differences in their hydraulic conductivity and defined in GOCAD as "regions." This allowed inhomogeneities to be identified within specific stratigraphic units. The gridded parameter models were transferred to the USGS MODFLOW software (USGS, 2005), which offers an integrated modeling environment for the simulation of groundwater flow, transport and reactive processes.

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Figure 21-9 NEAR HERE
Fig. 21-9. Flow diagram of stepwise model construction. Numbers correspond to steps defined in the text. (Modified from Panteleit *et al.*, 2013)
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In summary, the model construction involved a six-step process (Figure 21-9). The six steps are as follows:

<u>Step 1: Spatial configuration of cross sections</u>: GIS technology was used to define desirable locations for 121 geological cross sections, 48 for the Bremerhaven area and 73 for the city of Bremen. Data queries identified about 1150 of the deepest *reference boreholes*; these defined preferred cross-section intersections. Cross sections were oriented to represent the deep Elsterian melt-water channels. Throughout the construction process the borehole data were quality checked and assigned a quality rating ranging from class Q1 (the best quality data, reference boreholes) to Q5 (data unsuitable for modeling). Boreholes with a total depth of more than 25 meters and associated geophysical logs were particularly suitable as reference data points and thus given a high-confidence classification (Q1). *Gamma-ray* and resistivity *geophysical logs* were used to *determine the tertiary –quaternary transition.*

<u>Step 2: Stratigraphic interpretation and construction of cross sections</u>**:** All potential *reference boreholes* were subjected to further stratigraphic interpretation using the GeODin software (Fugro Consult GmbH, 2016). Digital cross sections were constructed by correlating stratigraphic boundaries identified in *reference borehole* logs to define the base of each hydrostratigraphic unit. Interfingering lenses had top

and bottom horizons digitized. The digital cross sections and selected borehole horizon markers were stored in a special database.

Step 3: Incorporation of *"free wells*": More than 34.000 deep boreholes and wells and were not used to construct the cross sections. These wells, defined as *"free wells"*, provided valuable additional control to the definition of the stratigraphic surfaces. The petrographic descriptions of each layer in these "free wells" assessed and assigned quality ratings from Q2 to Q4 according to their quality. A Q4 rating was assigned to boreholes with stratigraphic horizons identified solely from geophysical logs; a Q5 rating was assigned to boreholes with information deemed unsuitable for the model construction process.

Step 4: Construction of stratigraphic horizons: The *reference boreholes* and associated digitized horizon vertices on the cross sections were set as *"control nodes"* during the construction of each horizon in GOCAD. They were not allowed to move during the interpolation process and stratigraphic horizons were forced to pass through their locations. In contrast, interpreted horizon vertices from the cross sections and stratigraphic positions identified in the imported *free wells* were used as *"control points"*. *Control points* influence the geometry of the interpolated surfaces according to user-defined criteria, but the horizons do not have to absolutely match them. Based on these *"control nodes"* and *"control points"*, horizons were modelled using the GOCAD DSI (Discrete Smooth Interpolation) procedure Mallet, 1992; 1997). The resulting surfaces were relatively smooth, with minimal deviations from *control points*. Misinterpretations of borehole stratigraphy resulted in obvious surface irregularities; when observed, the borehole interpretations were corrected and the surface recalculated. The model base horizon (top of the Tertiary) had less available borehole information, so information from regional maps was used to guide its interpolation. The ground surface forms the top of the model. A 25 m resolution Digital Elevation Model (DEM) defined the ground surface.

Step 5: Construction of stratigraphic grids: The hydrostratigraphic horizons defining the model units were converted to a regular stratigraphic 100 x 100 m grid (GOCAD S-grid) by vertically associating the top and base horizons of each unit and dividing the distance between them into several layers according to the thickness of the unit and its heterogeneity (Figure 21-10A). Thus, the vertical resolution of the model varies, and Table 21-5 provides the range of the vertical resolution for each layer. To maintain continuous layers across the model, were a unit does not exist; it was defined as being 0.1 m thick.

Step 6: Parameterization of grid cells: In preparation for the groundwater flow modeling, each cell in the 3-D grid model was assigned appropriate parameter values based on its stratigraphic unit and property values stored for each well-log in the GDfB borehole database. This "parameterization" of the model converted lithologies to values of heat conductivity, permeability, or remediation potential (Figure 21-10B). These parameters were interpolated within the hydrogeological units from well-log observations imported into GOCAD using DSI and 3-D kriging operations supported by GOCAD.

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Figure 21-10 NEAR HERE

Fig. 21-10. Extract of the gridded geological framework model, showing: A) hydrostratigraphic units; B) parameterized hydraulic permeability model with values interpolated from borehole data. (Panteleit *et al.*, 2013)

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3.2 Groundwater Flow Model

A 3-D steady-state discrete-element regional groundwater flow model was developed using the 3-D geological framework model described in the previous section. The flow modeling was accomplished using MODFLOW with different graphical user interfaces as PMWIN (Chiang, 2005) or the open source FREEWAT platform for QGIS (Rossetto, 2015) and necessary pre- and post-processors. The flow model has 38-layers, corresponding to the number of layers defining the units in the geological framework model, and has the same 100 x 100 m grid size.

A gateway developed by McDiarmid (2011) allowed the rapid data transfer of parameterized GOCAD grid models to MODFLOW. Panteleit *et al.* (2013) provide details of the model hydraulic parameters. Each cell was assigned a hydraulic conductivity based on the "parameterization" derived from the lithologic borehole description (Fuchs, 2010). Vertical hydraulic conductivity was valued at nine-tenth the horizontal hydraulic conductivity by model calibration. Effective porosity, initial heads and boundary conditions were applied to the model by analyzing external sources. Modeled groundwater levels were verified by about 843 observation wells and water gauges. Groundwater levels are controlled by drainage in the low-lying agricultural areas and the water level of the river Weser.

3.3 Higher-Resolution Local Geological Framework Models

Several smaller areas experience severe groundwater contamination. In order to evaluate and manage these pollution plumes, a series of local and higher-resolution 3-D geological framework models were developed for these areas, including Bremen (Figure 21-11). These models have in general the same hydrostratigraphic units as the Bremen model, but have a finer grid resolution of down to voxels of 2.5 x 2.5 x 0.2 m. They also were based on more detailed interpretations of inherent heterogeneity conditions within the hydrostratigraphic units. Local groundwater flow modeling was performed using parameterized versions of these models.

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Fig. 21-11. Refined 3-D geological framework models for local areas with specific groundwater contamination problems. Four local areas are shown. (Seiter & Panteleit, 2016)

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3.4 Stochastic Simulations of Heterogeneity

To model the transport and reaction of a contamination plume in the heterogenic Holocene deposits flow modeling described in the previous section was not able to adequately define the contamination plume. Analysis of the extent and potential future growth of the plume required a more detailed definition of subsurface heterogeneity. Using observed boreholes, stochastic simulations (see Chapter 13) of the 3-D distribution of clay lenses produced a series of equally-likely subsurface models (Figure 21-12). In areas with insufficient or irregular distributed observations, stochastic simulations were developed from a combination of actual boreholes and randomly-placed virtual boreholes (Figure 21-12B).

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Figure 21-12 NEAR HERE

Fig. 21-12. Examples of detailed evaluations of subsurface conditions using stochastic modeling of heterogeneity: A) model based on 216 actual wells; B) model based on 216 actual wells and 218 virtual wells. (Seiter & Panteleit, 2016)

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These stochastic simulations of aquifer heterogeneity formed the basis for a series of parameterized grid model that permitted multiple assessments of the extent and growth of contaminant plumes. The transport and reaction model MT3D, accessed through PMWIN, performed these assessments. The model solutions compare very closely to the measured data or the observed contamination plumes.

4. APPLICATION OF THE MODELS

While geology and the models are certainly 3-D, typical users prefer 2-D derivative products, generally maps, printed or online. Some applications, based on a 3-D evaluation of the appropriate model, have produced user-friendly maps with distinctive topics such as “potential for enhanced rainwater infiltration” or “thermal conductivity and possible depth limitations for borehole heat exchangers” (Figure 21-13). True 3-D applications, such as groundwater flow-model results, are designed for use by expert users; thus, these applications are supplied with restrictions to specific user groups.

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Figure 21-13 NEAR HERE

Fig. 21-13. Examples of three 2-D open-access web-based application maps. (A) Potential for enhanced rain water infiltration – based on near-surface permeability and depth to water; (B) Building ground quality – based on organic soils and location of marsh areas; (C) Geothermal conductivity – an important parameter for assessing geothermal potential. (Seiter & Panteleit, 2016)

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Many 2-D derivative products are provided free-of-charge for use by any interested person through open-access via the World Wide Web. These products provide quick information for such topics as:

- **Potential for enhanced rain water infiltration:** To enhance the groundwater recharge and minimize impacts of heavy rain events, residents are charged reduced sewage water fees if they infiltrate collected rain water directly onto their property (Figure 21-13A).
- **Building ground quality:** In Bremen, building site quality is often adversely impacted by compaction of peat layers or highly organic clay soils. Disposal of these soils is expensive due to oxidation of pyrite and production of acid contamination. The Holocene units in the 3-D geological framework model were analyzed to produce a 2-D map showing the thickness of organic rich sediments (Figure 21-13B).
- **Geothermal potential:** The Bremen area is increasingly using shallow geothermal systems with heat exchangers (commonly probes) down to a depth of up to 250 m (see Chapter 22 for examples of 3-D models supporting geothermal assessments). Information on geothermal conductivity (Figure 21-13C) and basic groundwater flow-rates are provided as web-based maps.
- **Corrosive groundwater:** In some areas of Bremen, the groundwater is corrosive to concrete due to the high levels of ammonia, magnesia, and sulfate, or low pH. The Bremen borehole database provided information on corrosive potentials; these are displayed as data points by a web-map service.
- **Flooding risk:** There is a risk of flooding by the Weser River. A map was produced that defined areas below the highest documented flood level and locations of identified flood deposits.

Additional 3-D evaluations, based on appropriate models, are designed for use by enterprises and/or consulting engineers, who can utilize detailed subsurface information and the geological framework to develop more detailed groundwater flow models (Panteleit *et al.,* 2013). Potential applications include:

- Improved leakage inspection of sewer systems.

- Installation of industrial production wells.
- Design of large geothermal heat exchanger systems.

Some data and evaluation services are only available for government administrators, so are provided online with a restricted access. The 3-D models provide a strong management tool for:

- Evaluating groundwater or geothermal production well requests.
- Evaluating restrictions in groundwater catchment areas to protect public water supplies.
- Assuring the supply of raw materials for the construction industry.
- Assessing the impact of climate change on groundwater availability (Panteleit *et al.*, submitted).
- Establishing limits for temporary artificial changes in groundwater levels.
- Incorporating 3-D geologic and hydrogeologic parameters in land use planning.
- Forecasting flow paths when monitoring contaminated areas.

5. CONCLUSIONS

In Bremen, a large number of relatively deep boreholes supported the development of 3-D geological framework models and derived groundwater flow models. These permit a wide range of geological evaluations. Model development required a strict digital coding of the borehole data and a logical verification of geologic interpretations. Model construction involved 3-D development of cross sections used implicit modeling procedures, employed by GOCAD, to define the 3-D stratigraphic surfaces rapidly and efficiently.

The Bremen 3-D geological framework models and derived groundwater flow models successfully provided better and easily accessible management tools for spatial information. Many products are provided as 2-D maps offered free-of-charge to the public, industry, and government administrators through web-services. More sophisticated 3-D products support enhanced planning and design support to construction projects, geothermal installations, and groundwater resource evaluations. Additional analyses with contaminant transport and reaction models permit the enhanced monitoring and prediction of the extent of contamination plumes over time.