From the Devonian to the present: Landscape and technogenic relief evolution in an urban environment

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Abstract: A detailed geo-scientific knowledge of the subsurface in highly populated areas is essential for sustainable urban management and strategic planning, in terms of revitalisation of contaminated sites, groundwater protection, the assessment of engineering conditions, mining resources, and the preservation of archaeological sites. Nevertheless, systematic geological surveys in the past more or less excluded urban areas, as information is limited and the geo-environment, typically has been modified by anthropogenic-landscaping, most often since pre-historic times.

Existing heterogeneous data collections, mostly gathered during individual drilling campaigns, are not a straightforward information pool for decision makers and other end-users, as they have to be re-interpreted by experts for each purpose. With advances in digital visualisation and modelling techniques geologists are now able to express their knowledge of the subsurface in easy-to-use and easy-to-understand 3D models.

Recent studies in the eastern districts of Cologne focused on an interdisciplinary approach, by using geological maps, drill-logs, digital terrain data, historical maps, and archaeological subsurface data for the 3D mapping campaign. For the data visualisation, processing, analysis and modelling, the GSI3D-methodology and the respective software-tool have been used.

The established 200 km² 3D model includes detailed information on the distribution, lateral and vertical extent of geological units ranging from the Devonian basement, Tertiary lignite/sand/clay sequences, Quaternary fluvial cycles as well as the characteristics and the distribution of man-made ground.

These scientific results give base, top and thickness maps of aquifers and aquitards, thematic maps on engineering conditions and mineral resources. They form the base for further geo-environmental analysis, monitoring and forecasts. The established geo-scientific 3D model of the eastern parts of Cologne provides an holistic tool to be used by consultants, planners and decision makers for generating sustainable environmental management plans, to protect and/or improve, the natural and built environment and cultural heritage.

Résumé: Les études récentes dans les quartiers est de Cologne se sont concentrées sur une approche interdisciplinaire, en employant des cartes géologiques, des diagraphies, des données numériques de terrain, des cartes historiques, et des données archéologiques pour la cartographie trois-dimensionnelle. Pour la visualisation, le traitement, l'analyse et la modélisation de données la méthodologie et le logiciel GSI3D ont été employées.

Le modèle établi de 200 km² inclut des informations détaillées sur la distribution et l'extension latérale et verticale des unités géologiques, s'étendant du Dévonien jusqu'au Quaternaire, ainsi que des caractéristiques et la distribution du sol artificiel.

Ces résultats scientifiques donnent la base, le dessus et l'épaisseur des aquifères et des aquitards, ainsi que des cartes thématiques sur les conditions géotechniques et les ressources minérales. Ils forment la base pour des analyses additionnelles, la surveillance et les prévisions géo-environnementales. Le modèle 3D géoscientifique établi pour les quartiers est de Cologne ressemble à un outil holistique à employer pour développer un plan de protection et de gestion de l'environnement naturel et artificiel.

Keywords: 3D models, data visualisation, geodata, geology of cities, land use, mapping, urban geosciences.

INTRODUCTION

Modern societies create a growing stress on natural resources of the shallow and medium deep subsurface, especially in urbanized areas. Due to concurrent usage, environmental and engineering factors, contamination, natural and man-made hazards exist. It is necessary to establish strategies for the sustainable management of the natural environment and to provide a facility to visualise the complexity of the geological subsurface and its hazards to urban and regional planners, including decision and policy makers. This information is best provided by detailed, easy-to-understand, already interpreted, geo-scientific three dimensional models. These decision supporting 3D models have to be obtained from economic time and cost survey campaigns using multi-disciplinary investigation strategies, incorporating all available geo-scientific and related data, e.g. from archaeological, historical, geographical, morphological, geological, hydro-geological, geo-chemical, geo-technological, and geophysical databases. A detailed geo-scientific knowledge of the subsurface in highly populated areas is essential for sustainable urban management and strategic planning, in terms of revitalisation of contaminated sites, groundwater protection, assessing engineering conditions and mining resources, and the preservation of archaeological sites.

However, systematic geological surveys in past decades more or less excluded the investigation of the subsurface of urban areas, as data are limited and typically the geo-environment has been modified by anthropogenic landscaping, often since pre-historic times. In addition, existing heterogeneous data collections, mostly gathered during individual drilling campaigns, do not provide a straightforward information pool for decision makers and other end-users, as they have to be re-interpreted by experts for each purpose.

Advances in information technology, such as GIS systems, allow the visualisation of combined data sets, but only in 2D. In the past years several three dimensional GeoScientific Information Systems (GSIS) have been developed, mostly for individual and specialized geological applications. The 3D structure-models presented here have been established using the GSI3D (Geological Surveying and Investigation in 3D) methodology and software-tool. GSI3D enables all available 2D and 3D geo-scientific records to be integrated and visualised, creating a consistent and homogeneous data pool. This data pool is used to construct 3D models of the subsurface, which can then be analysed using various analytical functions. Using the digital visualisation of the structure-models and the distribution of the models via the SUBSURFACEVIEWER, geologists are now able to express their knowledge of the subsurface to non-geologists in easy-to-use and easy-to-understand 3D models which can themselves be applied as geo-scientific decision support tools for further usage in administrative units.

Recent studies in the eastern districts of Cologne focused on an interdisciplinary approach to the 3D mapping campaigns, by using geological, hydro-geological, engineering, and historical maps as well as drill-logs, digital terrain data, and archaeological surface and subsurface data. The geological and/or man-made inventory of four areas of investigation (Figure 1) has been mapped in three dimensions. The 3D maps cover an area of approximately 200 km², where each study concentrated on differing aspects of the geological and anthropogenic setting:

- Mülheim: general 3D mapping campaign of the geological setting,
- Porz: Tertiary detailed model,
- Airport Cologne/Bonn: Quaternary detailed model
- Kalk: Detailed model of anthropogenic modifications.

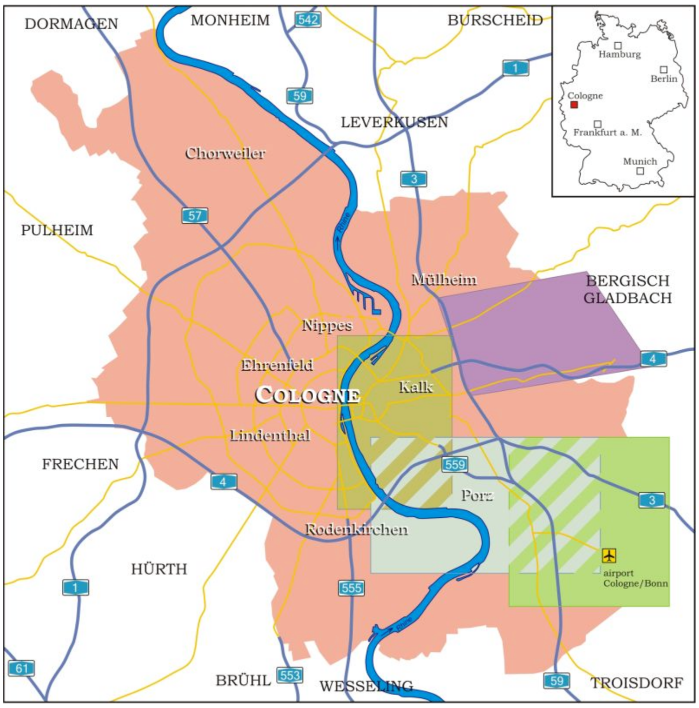

Figure 1. Location of Cologne and areas of investigation (purple: Mülheim, blue: Porz, light green: Airport Cologne/Bonn, dark green: Kalk).

GEOLOGICAL SETTING

Cologne is situated in the SE of the Lower Rhine Basin on the so-called Cologne Block (Kölner Scholle), east of the margin to the Rhenish Massif. The Lower Rhine Basin is a NW-SE orientated tectonic basin, divided by NW-SE striking main faults, into five blocks with differing subsidence rates. Subsidence in the Lower Rhine Basin started in Early Oligocene and continued to the Pleistocene, with the main tectonic activity in the Pliocene and Pleistocene.

The Lower and Middle Devonian basement of the Lower Rhine Basin, is covered by Cenozoic sediments. Tertiary sediments, predominantly from the Oligocene, Miocene and Pliocene, comprise marine sands and terrestrial clays with intercalated lignites (Figure 2). The maximum thickness of the sediments is 1,300 m in the Erft Block. The overlying Quaternary sediments, predominately gravels, sands and clays of fluviatil origin, have been deposited by the Rhine-Maas river system.

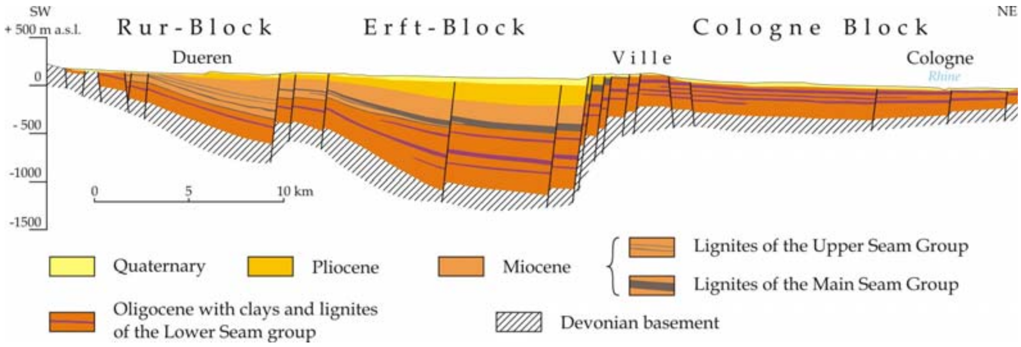

Figure 2. SW-NE oriented cross-section of the Lower Rhine Basin, after Quitzow (1966).

METHODOLOGY

The construction of structure-models, using the GSI3D methodology, is largely based on geo-scientific subsurface information from boreholes and outcrop information from geological and soil maps. The down-the-hole data are used to build up a net of consistent cross-sections, defining the spatial distribution as well as top and base of each geological unit present. These geological units, defined according to their lithological and stratigraphical characteristics and geological structures, are constructed by reference to genetical and morphological rules and perceptions. An iterative modification and fitting of intersecting cross-sections allows the generation of reasonable geological subsurface structures, e.g. channels, basins, swells etc.

Once the distribution and base of each geological unit has been defined in the cross-sections, these 2D correlation lines are triangulated into unit distributions, giving the lateral extent and the depth of the base of each geological unit. Volume bodies of each geological unit are subsequently calculated by stacking the base of each defined unit to the base of the covering unit. This also generates the thickness of each geological unit as well as the elevation of its upper surface. Volume body calculations commence from the youngest unit downward, where the Digital Terrain Model defines the top of each outcropping unit.

More details about the required and possible additional data sets for the 3D mapping process, on program internal calculation procedures, as well as GSI3D analysis functions are given in Sobisch (2000), Howahr (2003), Schade (2003), and Kessler et al. (in press).

RESULTS

The 3D geological, and partially the anthropogenic setting, has been studied in four exemplary areas in the eastern parts of Cologne (Figure 1). Each individual working area was investigated with an emphasis on a different aspect of the natural or man made environment.

Research in the 40 km² area south of Mülheim was performed, to get an overview on the general geological setting of the region, and to establish a best practice guideline on the usage and modification of 3D geological information in digital formats, directly during the field mapping campaign. The area consists of large agricultural dominated areas as well as various smaller towns, the latter inhibiting detailed geological surface studies.

The investigation of the area of Porz, 60 km² in size, was focused on the Tertiary sediment sequence. Surface outcrops are non- existent, thus all unit distributions had to be reconstructed from drill-hole data.

The Airport Cologne/Bonn study area is also 60 km² in size. Due to large-scale construction work for the airport, the regional landscape and geological environment is greatly modified. The research here, focused on the lateral distribution of the Quaternary fluviatile deposits, with a special emphasis on their stratigraphy.

The studies in a 40 km²-wide area in Kalk and surrounding parts of the city, concentrated on the establishment of a best practice guideline, for the characterisation and the 3D mapping of man-made ground.

For the area under consideration, in the eastern part of Cologne, nearly 16,000 boreholes and around 600 archaeological surface excavation reports have been processed and evaluated for the purpose of 2D cross-section construction. The data was either gathered from the Office for Soil and Groundwater Protection - (City of Cologne), or provided by the Geological Survey of Northern Rhine Westphalia and the Roman-German Museum of Cologne. The drill-logs derived from various investigations undertaken in past decades, ranging from environmental and engineering explorations to strictly scientific surveys, covered depths of up to 400 m below surface. The Digital Terrain Model from the City of Cologne, which was used, has a horizontal resolution of 5 m and a vertical accuracy of up to four decimal places.

Mülheim

A high-resolution image of the geological succession from the Middle Devonian to the Holocene was established in a 40 km² area south of Mülheim, in the eastern part of Cologne, by using drill-logs, as well as digital thematic maps - (topographical, geological, hydro-geological maps). More than 100 intersecting user-defined cross-sections have been constructed to cover all the strata forming the shallow and medium deep surface. In general, outcrops are scarce, as man-made deposits cover the geological strata. Hence, specific and detailed interpretation of the distribution of each stratum is not straightforward. The 3D mapping campaign proved to be the best method of analysing the geological environment within this anthropogenically modified region.

In order to verify the constructed unit distributions obtained from the structure-model, fieldwork was carried out. Expected outcrops and subsurface unit boundaries have been exported from the 3D model and have been verified and modified directly in the field, by using digital equipment (GPS, Pocket PC with ArcPad 6.0). In that way, sample records (including location coordinates, lithology, stratigraphy, depth, colour or moisture) could be directly integrated in the existing GIS-infrastructure. An obvious difference to conventional surveying practice was the ability to plan the field campaign beforehand, in more detail, and efficiency was increased as all data could be visualised and analysed in relation to all other geo-scientific information available.

The resulting stratigraphical succession, thickness and distribution of the geological units in an exemplary part of the area of investigation is shown in Figure 3, displaying the geological setting from the Devonian to the Quaternary in more detail than is possible with analogue geological maps.

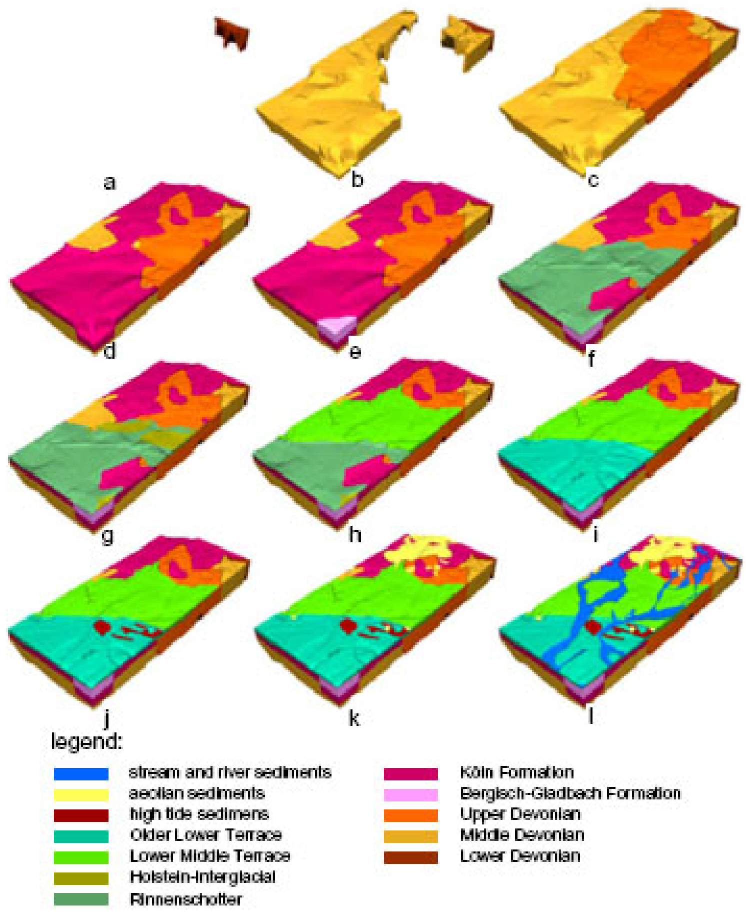

Figure 3. Stratigraphical succesion, thickness and distribution of the geological units south of Mülheim in an exemplary part of the investigation area. a) Lower Devonian in the SE, b) + Middle Devonian, c) + Upper Devonian, d) + Bergisch-Gladbach Formation (Tertiary), e) + Cologne Formation (Tertiary), f) + "Rinnenschotter" (Quaternary), g) + Holstein-Interglacial, h) + Lower Middle Terrace, i) + Older Lower Terrace, j) + overbank sediments, k) + aeolian sediments, l) + stream and river sediments.

Porz

Current studies in the south-eastern part of Cologne focus on a 60 km² area including the west of Cologne/Bonn airport and the districts of Porz and Rodenkirchen. About 4,000 bore logs, ranging in depth from 1 m to 400 m, have been used for the construction of cross-sections.

Initial cross-sections have been constructed using boreholes deeper than 100 m, covering geological units from the Devonian, Tertiary and Quaternary sequences. These cross-sections are generally orientated, north to south and east to west. Near-surface boreholes have been used to construct additional detailed Quaternary sediment sections. Altogether 11 cross-sections have been constructed to cover the deeper surfaces down to the Devonian, and a further 12 cross-sections for detailed 3D mapping of the Quaternary units. 10 supplementary cross-sections have been constructed with an emphasis on the Tertiary sediments.

The construction of the Tertiary strata has been based on bore logs of over 50 m in depth. In order to obtain sufficient information on the regional tectonic setting, and the stratigraphy of the Cologne Block, it has been necessary to use bore logs, which lie outside the actual area under consideration. These were distributed widely in the eastern part of Cologne from Troisdorf in the south to Cologne-Mülheim in the north (Figure 1).

The basement of the Cologne Block comprises Lower and Middle Devonian sediments. The Tertiary strata are represented by the Bergisch Gladbach-Formation (upper Rupelian) and the Cologne Formation (Chattian to Aquitanian). The continental Bergisch Gladbach-Formation occurs in the area of investigation at the base of the Oligocene sediments an argillaceous-lignitic and sandy facies. The clays and lignites are exceptionally thick where they occur in former sink-holes in the limestones of the Bergisch Gladbach-Paffrath Syncline. The facies of the Bergisch Gladbach-Formation relate to the Devonian rocks at their base; argillaceous-lignitic in areas associated with calcareous Middle and Upper Devonian sediments, and sandy lithology in areas associated with clastic Lower Devonian sediments.

The Cologne Formation, in the area under consideration, is represented by the horizons 05 up to 3 (nomenclature after Schneider & Thiele, 1965) with marine fine and middle sands originating from transgressions of the "North Sea" in the Lower Rhine Basin during the upper Oligocene. The intercalated clays and lignites are of continental origin and represent deposits of intervening marsh and lagoonal environments.

The marine sands of the Cologne-Formation, in general, are light grey fine sands lacking coarse grained or argillaceous horizons. The horizon 07 is an exception with an intercalated 4 m thick clay horizon in the lower part of the sequence. This horizon is found only in the eastern part of the study area (Figure 4). In the west, it thins out into a fine sand dominated horizon. The distribution of the clay horizon, in the north of the area of consideration, cannot be reconstructed in detail, due to the lack of borehole information. The facies of the clay horizon change in the southeast from argillaceous to lignitic. The occurrence of a clay horizon in the marine sands of horizon 07 has not previously been described in the literature. Due to the palaeogeographic setting of the southern Lower Rhine Basin, in the Chattian, this clay horizon is interpreted as a lagoon. The horizon 07 was deposited during a marine transgression on a wave dominated high-energy coast. The eastern part of the study area appears to be a former coastline, whereas more to the west, a barrier island existed that bordered the lagoon. During the transgression, the coastline advanced in a SE direction and fine sand buried the lagoonal clay. The lignitic part of the clay horizon, in the SE, represents the transition to a marsh environment.

The marine horizons 07, 09 and 2 of the Cologne-Formation show a change in colour from light grey in the lower part to dark brown in the upper part. This change is caused by humic acid-rich groundwater infiltrating from the terrestrial clay and peat horizons above the marine sand horizons; the humic acids in solution, precipitate due to pH-value changes and form brownish coatings on surfaces of the sand grains.

A correlation of the Cologne-Formation horizons, solely by petrographic features, is not possible, as the lithology of the intercalated sand and clay horizons is in general always similar. However, the terrestrial clay and lignites, in horizons 06, 08, 1 and 3, display distinct, constant, and characteristic thicknesses. Hence, it has been possible to correlate these horizons using the clay thickness as a reference. This proved especially true for horizon 1, with two or three characteristic lignite horizons (Figure 4). This is a characteristic marker horizon in the southern Lower Rhine Basin.

The maximum thickness of Tertiary deposits is 365 m in Rodenkirchen, in the western part of the study area. The Cologne-Formation is in the form of a gentle syncline in the area of Cologne, dipping in westward direction at less than 1°. The evolution of the syncline started in the Upper Oligocene and ended in the Middle Miocene. The segmentation of the syncline, by NW-SE striking faults, started after the deposition of the Cologne-Formation, in the Middle Miocene. The main tectonic activity in the Lower Rhine Basin occurred during the Pliocene and the faults developed to their present state. The undisturbed Quaternary sediments indicate that there was no tectonic activity in the area under consideration in the Pleistocene and Holocene.

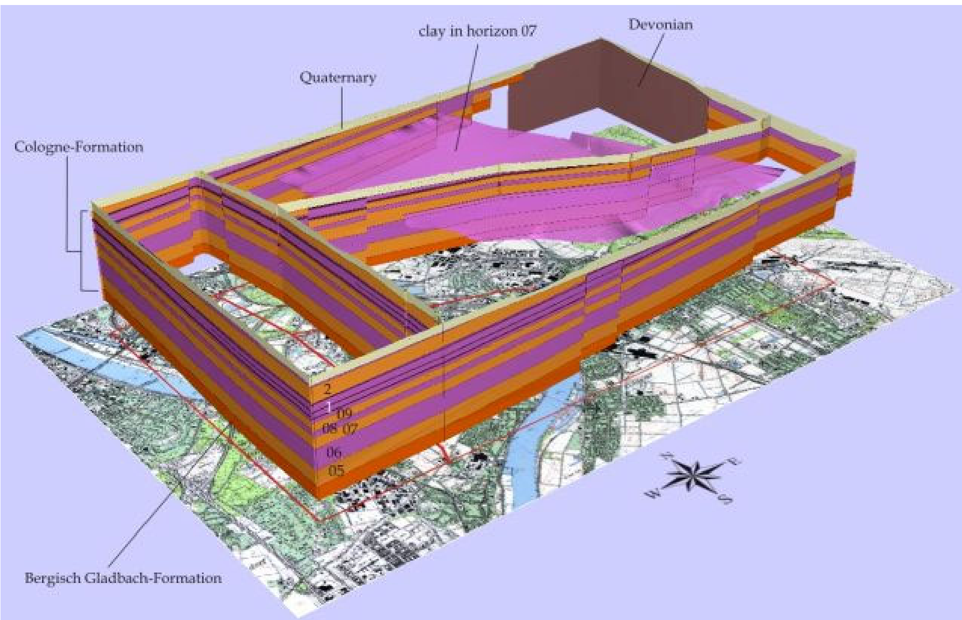

Figure 4. Fence diagram of the Tertiary strata in the study area of Porz showing the location of the lagoonal clay in horizon 07. Tertiary nomenclature after Schneider & Thiele (1965).

Airport Cologne/Bonn

Geological studies of the Quaternary fluvial strata of the Lower Rhine Embayment, since the late nineteenth century, form a spectrum of increasingly detailed and sophisticated, but controversial models. In particular, the stratigraphical position of a gravel, defined as “Rinnenschotter” by Quitzow (1956) is still under discussion.

The current investigation, in the area of Airport Cologne/Bonn, focused on the interpretation of the depositional system in the south-eastern part of Cologne. This was in order to obtain a better understanding of the stratigraphic succession of the Middle Terrace deposits. Several hundred bore-logs have been used to construct 26 cross-sections extending from the Pleistocene down to the Tertiary, as well as to resolve the distribution and elevation of the so-called “Rinnenschotter”.

The southern part of the Lower Rhine Embayment is a region of significant tectonic uplift during the Pliocene and Pleistocene, with resulting well-developed terrace staircases. These staircases were formed by cyclic down-cutting and accumulation. Resulting climatic changes and progressive uplift, exposed the Middle Terrace Sequence within this area (MT II, MT IIIa (“Rinnenschotter”), MT IIIb after Brunnacker et al. (1978) and the intermediary Holstein-Interglacial; Figure 5).

The 3D mapping of the MT IIIa (“Rinnenschotter”) undertaken, shows that the definition of the MT IIIa as a separate terrace after Klostermann (1992) is rather unlikely. Based on the accumulation cycle of the individual Middle Terrace horizons identified in the study, - also described by Boenigk (1991, 1995), - the “Rinnenschotter” does not represent an individual terrace. Rather, the gravel body represents the glacial lower part of the sediment accumulation of the subsequent Holstein-Interglacial. Hence, the lower MT IIIa and the younger MT IIIb together form the Lower Middle Terrace (MT III).

Assuming, that this glacial accumulation is linear, glacial erosion must have occurred at the base of the MT IIIa (Figure 5a). The transition to the clayey and silty deposits of the Holstein is characterised by a primary interglacial erosion surface comprising channel structures on the top of the gravel body of MT IIIa (Figure 5b). Even though it is expected that after an interglacial deposition, erosion takes place, the constructed succession indicates a glacial accumulation of the MT IIIb (Figure 5c). Subsequently, the succeeding accumulation cycle of the Middle Terrace Sequence was deposited, itself concluded by further linear erosion forming the base of the Older Lower Terrace.

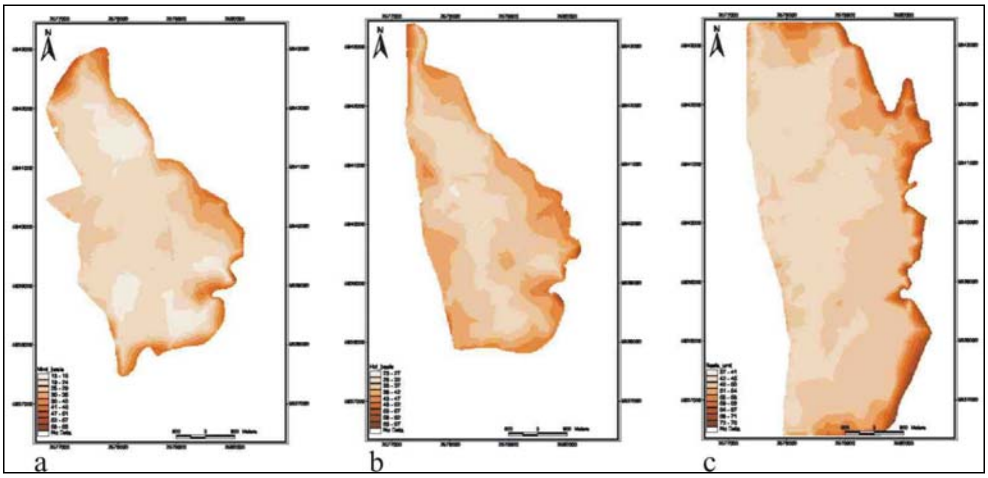

Figure 5. Thematic maps of the distribution and the depth of the base of the a) MT IIIa (“Rinnenschotter”), b) Holstein-Interglacial, c) MT IIIb.

In general, the deposition of the Middle Terrace sequence in the Lower Rhine Embayment is controlled by a glacial-interglacial-glacial-rhythm, starting with glacial erosion succeeded by an interim interglacial. The systematic cycle of the various warm-cold processes of accumulation and erosion can be reconstructed in a single stratigraphical unit, defined by thickness and base elevation maps (Figure 5) and block diagrams (Figure 6).

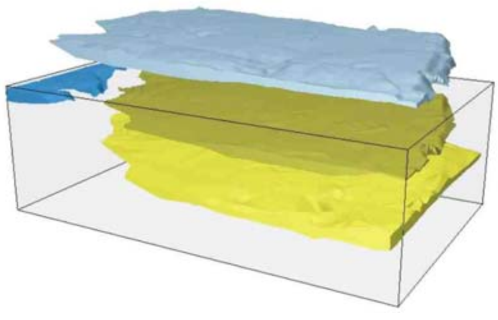

Figure 6. Exploded view of the Middle Terrace stratigraphic sequence (blue: MT II, yellow: MT IIIa (“Rinnenschotter”) and basal gravel deposits of MT III, green: Holstein-Interglacial, light blue: MT IIIb).

Kalk

Due to its long and intense history of settlement and occupation, which includes prehistoric, ancient, medieval and modern landscaping eras, the shallow subsurfaces of most middle European cities present complex and heterogeneous structures, with natural deposits of fluvial origin alternating with man-made deposits like waste, building rubble and war-wreckage. Within the study area, the Eastern District of Cologne, anthropogenic changes to the surface and subsurface strata can be traced back to Roman times. They comprise deposits filling a trench, which originally surrounded a Roman fort (Figure7).

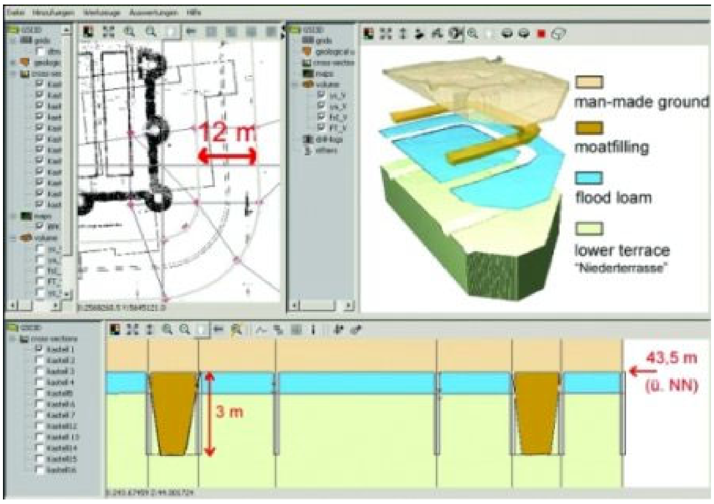

Figure 7. Structure-model of the surface and subsurface features in the area of a former Roman fort. The subsurface feature is covered by several 10's of mm to m of Post-Roman man-made ground. Its development was reconstructed by incorporating geological borehole data and data from archaeological excavations, which defined the elevation, depth, size and wall angle of the trench.

In order to reproduce and understand the complexity and heterogeneity of the shallow urban subsurface, a detailed interdisciplinary 3D map of the natural strata and man-made ground units and anthropogenic land-forms was generated using the latest surface and subsurface GSIS's. This work provided and enhanced guidelines and procedural methods for urban subsurface modelling. These best-practice guidelines cover various aspects of how to map artificial ground in an urban environment and range from conceptional to practical methods (Classon et al., 2005):

- One of the research tasks has been to investigate data-requirements and data validation methods required to produce the essential input datasets for 3D-modelling with GSI3D e.g. the qualitative requirements for digitised elevation data and the required down-hole data. Most borehole datasets lack essential information to define the uppermost man-made disturbed strata. This is due to the widespread lack and/or undeveloped standards for describing man-made ground. Therefore, suggestions on how to systematically address standards for describing man-made ground deposits have been introduced.
- Furthermore, techniques for data-processing have been educed, be it the management of a large amount of drill-log data, - inevitable for modelling urban subsurface conditions within an databank-management-system, - data manipulation by means of homogenisation, or the editing and improvement and analysis of digital terrain data.

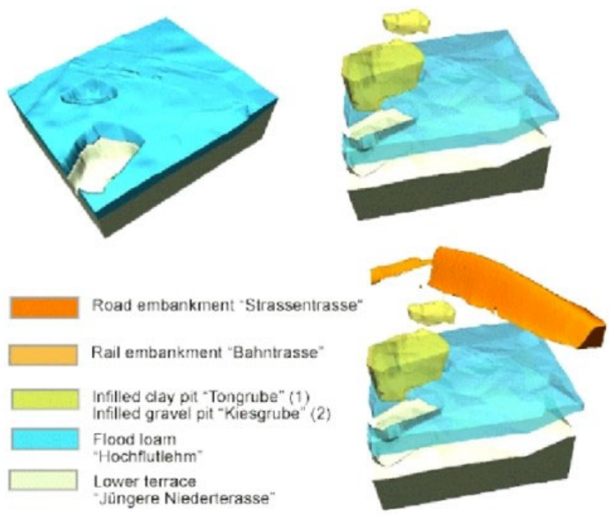

Figure 8. Structure-model of the surface and subsurface features in the area of a former minig area.

- Regarding the methodology of man-made ground modelling, the GSI3D-methodology - originally invented for spatial modelling of natural deposits - had to be enhanced. This is due to the depositional nature of man-made ground: man-made ground units do not have a genesis like sediments do. They do not follow sedimentological rules. Simply taking subsurface information it is not adequate to model their lateral and vertical extent. The only way to model the extent of man-made ground units, is to combine spatial subsurface data with surface data. The surface datasets are derived from time-lapse analysis focused on the 'excavation and aggradation history 'of e.g. historical and topographical maps. These are capable of defining the potential vertical extent of man-made ground units; for example the outcrops of former quarries, pits and dumps from mining-activity (Figure 8). Only by the use of such techniques can representative man-made ground units be incorporated into a subsurface model that can ultimately lead to a precise and holistic view of the urban subsurface.
- Published 3D-mapping of man-made ground is fairly immature, but gaining increasing importance. A contribution to the general issue of defining man-made ground and artificial form-systematisation has been made by introducing an enhanced, hierarchical, multilevel scheme for addressing, quantifying and qualifying man-made surface and subsurface elements. This is analogous to the litho-stratigraphical system for addressing natural deposits, ordered by group, formation and member, man-made deposits have been addressed using a hierarchical, sub dividable scheme - giving progressively more detail - comprising class, group, type and unit.

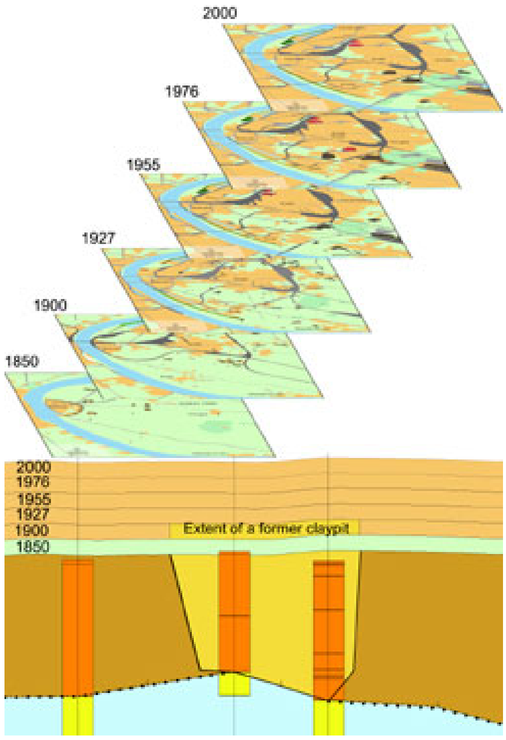

Figure 9. Technogenic land-use sequences from 1850 to present: Reconstructed from topographic maps. The structures and distribution of man-made ground deriving from the cartographical work provides potential boundaries and outcrops of artificial ground units. Multiple data sets, in combination with borehole information, are integrated into the structure-modelling process.

DISCUSSION

The landscape evolution and the geological and/or anthropogenic setting of four individual areas, covering up to 200 km² situated in the eastern parts of Cologne, have been mapped in three dimensions using the GSI3D methodology. Each study focused on distinct aspects of the natural and/or man-made environment, establishing best practice guidelines for the specific tasks at hand. By combining data sets of various geo-scientific and related sciences, it has been possible to reconstruct, in detail, the geology, as well as tectonic structures, from the Lower Devonian up to the Holocene. The natural environment has been mapped by distinguishing litho-stratigraphic characteristics for each unit from the available bore logs, using these log descriptions for the construction of cross-sections and subsequently generating a mesh of consistent cross-sections. This mesh of cross-sections defined the lateral distribution and thickness of each unit present and also displayed the genetic aspects of landscape evolution envisaged by the geologist. For 3D mapping purposes of man-made ground, a system for dealing with anthropogenic features and sediments of the geo-environment, set up by Price et al. (2004) has been used and enhanced. It is analogous to the litho-stratigraphical system used to describe a succession of natural deposits - ordered by group, formation and member, man-made deposits have been classified using an hierarchical, multilevel scheme, which is sub-dividable, giving progressively more detail. This comprised class, group, type and unit. The scheme not only takes the landform of man-made units and/or deposits into account, but also its functional origin and this allows one to systematically address, quantify and qualify the anthropogenic influence on the environment over time.

The use of multidisciplinary approaches to mapping in urban areas has shown, that even diverse and complex man-made superficial cover or modified or reworked geological successions and surfaces can be visualised in considerable detail both at the surface and at shallow and medium depths (e.g. Kessler et al., 2004).

Each field campaign accompanying the structure-models of the eastern parts of Cologne presented here, could be planned beforehand based on the established 3D model. In addition, questionable or dubious geological situations - visible from the combined visualisation of the morphology, geological maps and bore-logs in the model - could be addressed directly in the field. As a result, large scale and time-consuming surveys has not been necessary and costly intensive fieldwork has therefore been reduced to a minimum. Where applicable and necessary, the 3D models have been verified directly in the field via the modification of initially generated digital outputs of previously constructed geological unit distributions, stored in digital format on a Pocket PC. From the fieldwork the geologist had the newest version of the 3D structure-model already at hand. By applying the GSI3D methodology, office work consequent to the field campaigns, has been optimised.

The field verification also improved the accuracy of the 3D structure-models constructed from gathered archive data sets. One of the advantages in a 3D mapping system is the common visualisation of multidisciplinary information sets and their spatial relation in three dimensions, allowing new insights into the nature of the subsurface. The applied technique of constructing cross-sections is well known to geologists and the possibility to visualise each cross-section in the context of constructed model of intersecting cross-sections generates a powerful tool to help the geologist to understand the complexity of the geological system and build up the 3D model.

Advanced GSIS systems are able to visualise the geological subsurface in terms of the lateral distribution and thickness of each geological unit as well as the succession of the geological units. With GSI3D, or the related SUBSURFACEVIEWER, it is then possible to analyse the subsurface by e.g. creating geological maps, uncovered maps, thematic maps, user defined cross-sections, horizontal slices in any elevation and synthetic drill holes. The area and volume of each defined geological body can be calculated and further analytical functions allow one to integrate and visualise hydro-geological and engineering properties and parameters for each mapped (sub-)unit.

The homogenisation of multiple, mostly analogous, data sets, and their subsequent integration into the modelling process to form a 3D structure-model, also adds value to the existing database information. These heterogeneous data sets have mostly been gathered in the last few decades from numerous drilling campaigns, generally stored in various administrative bodies such as City Councils. Without the model, each data set has to be re-interpreted by specialists for each individual purpose, for which subsurface information is required, from small road construction works to large-scale subway and bridge construction. Gathering, homogenising, visualising, analysing and storing all these differing data sets in one GSIS system, ready-to-use for any of the end-user groups, enables the cost and time for planning individual campaigns to be reduced.

The models, which have been constructed and presented here, are not static "snapshots" of the geological situation relying on the data available during the time of model construction. The models are kept in a dynamic form; such that each newly gathered piece of geo-scientific information, - from e.g. new drillings, - can be added to the existing structure-model basic data set and the model can be modified according to this new information.

By implementing integrated investigation strategies and visualising the geological environment using digital 3D subsurface-models, such GSIS systems, provide decision support tools for consultants, water companies, planners and strategic decision makers. The gathered and interpretation-free applied geological data pool can be used to develop management strategies for a wide range of sustainable ground-related issues, e.g.:

- assessment of location, thickness and capacity of aquifers and aquitards,
- management of groundwater resources,
- monitoring of water quality and all related environmental issues,
- detailed risk assessment due to concurrent usage,
- integrated investigation strategies of contaminated (mega-)sites,
- support of licensing processes for water usage,
- protection of groundwater dependent eco-systems,
- implementation of the EU Water Framework directive,
- risk assessment of geogenic hazards,
- construction planning in urban areas.

The interpreted geological units of the 3D mapped areas presented above can now be, - (and already have been in parts), - integrated as exported grids and shape files into the common GIS systems of administrative units, planners, consultants or decision makers, or can be distributed in the form of 3D geological maps via the SUBSURFACEVIEWER for further analyses, processing and usage as a decision support tool.

SUMMARY

Nowadays, geological information in highly populated urban areas is more or less restricted to decade old geological maps and borehole log descriptions gathered and interpreted during individual drilling campaigns; mostly with an emphasis on a specific aspect of the geological environment. These heterogeneous collections of data are not a straightforward information pool for decision makers and other end-users of geological information, as they have to be re-interpreted by experts for each particular purpose. Nonetheless, decision makers, planners and administrative units do need a detailed knowledge of the medium deep and shallow subsurface, especially in urban areas, where concurrent usages create a growing stress on the natural environment as well as the cultural heritage.

The use of advanced 3D GSIS systems prior to and during mapping campaigns offers huge advantages, on the one hand by comparison with classic analogue methods and on the other hand in enabling effective homogenisation of heterogeneous archive data sets. The studies described here, were all based on the GSI3D methodology. GSI3D is a powerful tool to visualize the geological setting in former high energy environments, consisting of rapidly changing facies and small scale variations in lithology and stratigraphy. The software-tool enables geologists to integrate a large variety of geo-scientific data sets into the modelling process, and facilitates the application of their own genetic interpretation and knowledge in determining the evolution of the landscape and the environment. The result of the 3D mapping campaign has been the generationof a dynamic 3D structure-model, which generally displays the geological setting in more detail than a 2D geological map.

From the interpretation of bore log descriptions it has been possible to distinguish between deposits of the Lower, Middle and Upper Devonian and reconstruct the tectonic setting of these units. The orientation, estimated vertical offsets and the extension of individual faults and horst-structures has been integrated into the resulting 3D structure-model for the Devonian as well as the Tertiary. The Tertiary succession, represented by several marine sands and intercalated clay and lignite horizons, as well as minor faulting has been mapped in the subsurface in minute detail. Changes in unit thickness and lateral distribution have been identified as well as facies changes within the clay horizons from argillaceous to lignitic. Based on these interpretations of the environment of the medium deep subsurface it has been possible to reconstruct the paleogeographic setting of the southern Lower Rhine Basin in the area under consideration, e.g. former coastlines, lagoons and a marsh environments. The studies reported here, indicate that the depositional environment of the Middle Terrace Sequence was controlled by a glacial-interglacial-glacial-rhythm, starting with glacial erosion succeeded by an interim interglacial. Man-made ground has been assessed and characterised by applying a hierarchical, multilevel system, incorporating the functional origin, consisting of class, group, type and unit.

The integrated approach of the current study and the use of the GSI3D methodology and software-tool to visualise and map the geological environment in three dimensions offers the following advantages:

- a single software-tool for assessment, management and monitoring of the shallow and medium deep subsurface,
- cost reductions for planning and investigations due to efficient use of multidisciplinary archive material prior and during field campaigns,
- value added to existing data bases in task orientated and optimised work flows,
- spatial information data management and export capabilities to existing IT-infrastructures and of thematic maps to GIS systems,
- distribution of digital 3D geological maps via the SUBSURFACEVIEWER with analysis functions for further processing,
- visualisation and analysis of the subsurface, by the appropriate expert, - (usually geologist), - in order to deliver an easy-to-understand decision support system for policy and decision makers involved in sustainable regional planning.

In summary, the scientific results of the 3D mapping campaigns presented here have been used to distinguish the base, thickness and top of each geological unit in outcrops and in the subsurface from the Holocene to the Devonian as well as the functional classification of man-made ground. The constructed 3D structure-model allows, for example, base, top and thickness maps of aquifers and aquitards, thematic maps on engineering conditions and mineral resources to be extracted. These analytical results from the model form the basis for further geo-environmental analysis, monitoring and forecasts. Therefore, the established geo-scientific 3D model of the eastern parts of Cologne resembles an holistic tool to be used by consultants, planners and decision makers for generating sustainable environmental management plans to protect and improve the natural and built environment as well as the cultural heritage.

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