Brussels Urban Geology (BUG): a 2D and 3D model of the underground by means of GIS

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Abstract: The urban development and the restoration of the urban infrastructures currently plays a significant role in the conurbation of Brussels. The first aim of the Brussels Urban Geology (BUG) program is the creation of a GIS application gathering and collecting all information on the geological underground of the Brussels region. The ultimate goal is to create a tool usable by the local authorities and the companies within the framework of regional planning within the territory of Brussels.

Several databases have been created and will be illustrated in this paper:

- The drill holes database is used to build up the 3D geological model of the underground of Brussels. For all the boreholes, information is stored on the depth of the top and the thickness of each geological formation, the geographic coordinates, the type of the boreholes, etc.
- The fillings database will serve to create contour maps of the made ground observed in the boreholes of the Brussels region. This is particularly important in the urban planning development.
- The peat database identifies all the boreholes in which peat layers have been observed and aims to locate the zones where small ground movements could occur. The outputs from this layer inform about the thickness and the nature of peaty grounds and are thus particularly important in this context.

Currently, more than 700 drill holes, from a total of around 5000 drill holes available in the archives of the Geological Survey of Belgium (GSB), are integrated in the databank. By means of ESRI software products, these boreholes are then represented vertically in space in the form of several successive sections. Each section corresponds to a geological formation (twelve geological layers have beenidentified until now). The geological 3D model is built with ArcGIS 3D Analyst extension. It generates an interpolation of the top of each geological formation encountered in the Brussels underground.

Résumé: Le développement urbain et la restauration des infrastructures urbaines sont deux secteurs en pleine expansion dans l'agglomération bruxelloise. L'objectif principal du programme de géologie urbaine nommé « Brussels Urban Geology » (BUG) est de créer une application SIG regroupant et centralisant toutes les informations disponibles sur la géologie du sous-sol de la région de Bruxelles. Le but ultime est de présenter un outil utilisable par les autorités locales et les entreprises oeuvrant dans le cadre de l'aménagement du territoire à Bruxelles.

Pour cela, plusieurs bases de données ont été développées :

- La base de données des forages a été créée pour construire un modèle géologique 3D du sous-sol de Bruxelles. Pour chaque forage, l'information implémentée dans la base comprend la profondeur du toit et l'épaisseur des différentes formations géologiques traversées, ses coordonnées géographiques, le type de forage, etc.
- La base de données des remblais servira à dessiner une carte isohypse des remblais à partir des informations contenues dans la description des forages réalisés en région bruxelloise. La présence de remblais et surtout leur épaisseur sont deux informations importantes pour le développement urbain d'une agglomération.
- La base de données de la tourbe répertorie tous les forages dans lesquels la présence de tourbes a été mentionnée. Cette base est développée afin de localiser les zones où la présence de tourbes pourrait induire de petits mouvements du sol. La cartographie de cette couche permet de connaître l'épaisseur et la nature des terrains tourbeux, elle est donc particulièrement importante dans ce contexte.

Actuellement, plus de 700 forages des archives du Service Géologique de Belgique (SGB), sur un total avoisinant les 5000, sont intégrés dans la base de données des forages. Au moyen des produits d'ArcView, la base est importée dans le logiciel SIG; ces forages sont alors représentés verticalement, sous forme de plusieurs segments successifs. Chaque segment correspond à une formation géologique ; douze couches géologiques sont identifiées actuellement. Le modèle géologique 3D est ensuite développé à partir de l'extension 3D Analyst d'ArcGis. Ce modèle est le résultat d'une interpolation et représente le toit de chaque formation géologique rencontrée dans le sous-sol bruxellois.

Keywords: 3D models, geology of cities, database systems, geographic information systems, drilling.

INTRODUCTION

From an administrative point of view, a single region, with a surface area of 162 km², containing the 19 communes of Brussels was established in July 1971. This area was known as the "Agglomeration" of Brussels, and had authority in the areas of town and country planning, transport, safety, public health and cleanliness, economic expansion, etc. Since the 18 June 1989, the Brussels-Capital Region is an autonomous region comparable to the Flemish and Walloon Regions.

The urban re-development and the restoration of buildings are the two main processes, related to the urban evolution (growth of the population and evolution of the urban space) in the Brussels area.

During the 14^{th} century population of Brussels was only about 20.000 people. As in the majority of large European cities, it is only during the 19^{th} century that the population strongly increased, exceeding 1 million inhabitants in 2004. Brussels developed by space diffusion starting from the medieval city centre and suburban small villages included today in the Brussels-Capital Region. The urban growth was very fast between 1955 and 1985, reaching 600 ha/year on average, and decreasing gradually since (100 ha/year between 1985 and 1997).

The town of Brussels is cut into various sectors: large class of the wealthy population has been migrating to the periphery of the city (close to the Soignes forest for example), leaving many old quarters (along the axis of the Senne valley) occupied today by an underprivileged population. The restoration of these quarters and the continuous urban development require an important investment. In order to manage and to facilitate the realization of such works, a thorough knowledge of the underground is essential.

Two years ago, the Geological Survey of Belgium (GSB), located in Brussels, launched a new Geographic Information System (GIS) program called "Brussels Urban Geology" (BUG) focussing on the urban geology of the city. Brussels was selected as a pilot study to define a methodology for constructing a 2D and 3D GIS model of the subsurface geology. As a result, the GSB team has created an application with ArcGIS desktop (ArcView) software with which all the available data gathered could be stored in a database and managed within an open, dynamic and visual GIS. ArcView was chosen essentially for the 3D-Analyst extension accompanying the main software. The objectives of the program were to provide a geoscience basis for planning and development decisions. The users of the study were seen primarily as planners and developers but the results were also intended to be used by civil or company engineers, public administrations and others, providing concise, accessible advice on the relevance of geological conditions in the Brussels area to land use planning and urban development.

GEOGRAPHICAL AND GEOLOGICAL SETTING

The area of Brussels and more particularly the historical heart of the city are disected by the Senne valley following a SW-NE axis. Other valleys, less important and parallel with the Senne axis, like those of the Maelbeek and Woluwe, also incise the eastern part of the urban landscape of Brussels. The altitude difference between the top of the hills and the valleys can reach more than 80 meters. A large plain, gently inclined towards the north and formed by the alluvial deposits of the Senne river, lies at an altitude ranging between 19 m in the south to 13 m in the north. The 162 km² of the Brussels Region are covered by 6 topographic maps at 1:10,000 scale.

The region of Brussels is located above the Brabant Massif basement that covers almost 60% of the Belgium territory. The Brabant Massif consists of a compressed wedge whose core is formed by steeply deformed Cambrian formations (Sintubin & Everaerts 2002) that are flanked to the NE and SW by younger Ordovician and Silurian formations separated from the core by deep-seated shear zones (Piessens *et al.* 2004). The Brabant Massif was a persistent positive area with only reduced sedimentation during Late Palaeozoic time. Middle Devonian clastic and Dinantian carbonate sediments form a sedimentary cover with some gaps (Mansy, Everaerts & De Vos 1999 and references herein). The Carboniferous was probably removed by erosion during a Jurassic uplift (Vercoutere & Van den Haute 1993). Late Cretaceous chalk deposits (Senonian Age) are preserved. The Brabant Massif experienced an intensive phase of subsidence starting during the late Cretaceous. The deposits of sedimentary Tertiary marine series composed of clays, silts and sands occur during numerous eustatic cycles. The subsurface geology is detailed in the following paragraphs.

Anthropogenic fills are present almost everywhere and have a thickness ranging from tens of centimetres up to several meters. The Quaternary deposits are subdivided into two main layers. Firstly, modern Holocene alluvial sediments composed of loams, sands, clays, peat and gravels layers, are essentially located in the Senne valley and small adjacent valleys. The alluvial sediments are generally not suitable for the foundations of the buildings. Their thickness ranges generally between 10 and 20 m in the Senne valley. Secondly, the Pleistocene deposits (loess and fluviatile sediments) cover the whole area. Their thickness varies strongly from place to place and can reach up to 20-30 meters. Beneath the continental Quaternary sediments Tertiary marine formations are present spanning from the Upper Miocene down to the Upper Paleocene (Figure 1).

The Diest Formation (Di, Upper Miocene) and the Bolderberg Formation (Bo, Lower Miocene) correspond to small sand deposits at the top of the hills in the northern part of Brussels. These formations have been partly preserved from erosion and reach a combined maximum thickness of 27 meters. The Sint-Huibrechts-Hern sandy Formation (Sh) of the Upper Eocene has a reduced thickness in the north while in the southeast it can reach more than 10 meters. The Maldegem Formation (Ma, Middle Eocene) contains four members. The stratigraphic succession from top to base starts with the 2 m thick clay of Zomergem. The glauconitic grey sands of Onderdale reach a thickness up to 7 meters. These two members are only observed in the north of Brussels. The Ursel and Asse Member, 12 m thick, is composed of homogeneous grey to greenish clay. The grey, glauconitic sands of the Wemmel Member show an increasing content of clay towards the top. The Maldegem Formation is relatively good for house foundations except when it is saturated with water. The Lede Formation (Le, Middle Miocene), generally 12 m thick, is mostly present in the hills of the north, east and southeast parts of Brussels. The Lede Formation is composed of sands, sandy calcareous banks in the lower part and gravels at the base. Five to twelve sandy calcareous banks are present in the lower part of the Lede Formation and have been actively exploited in underground in galleries connected to shafts since the Middle Ages.

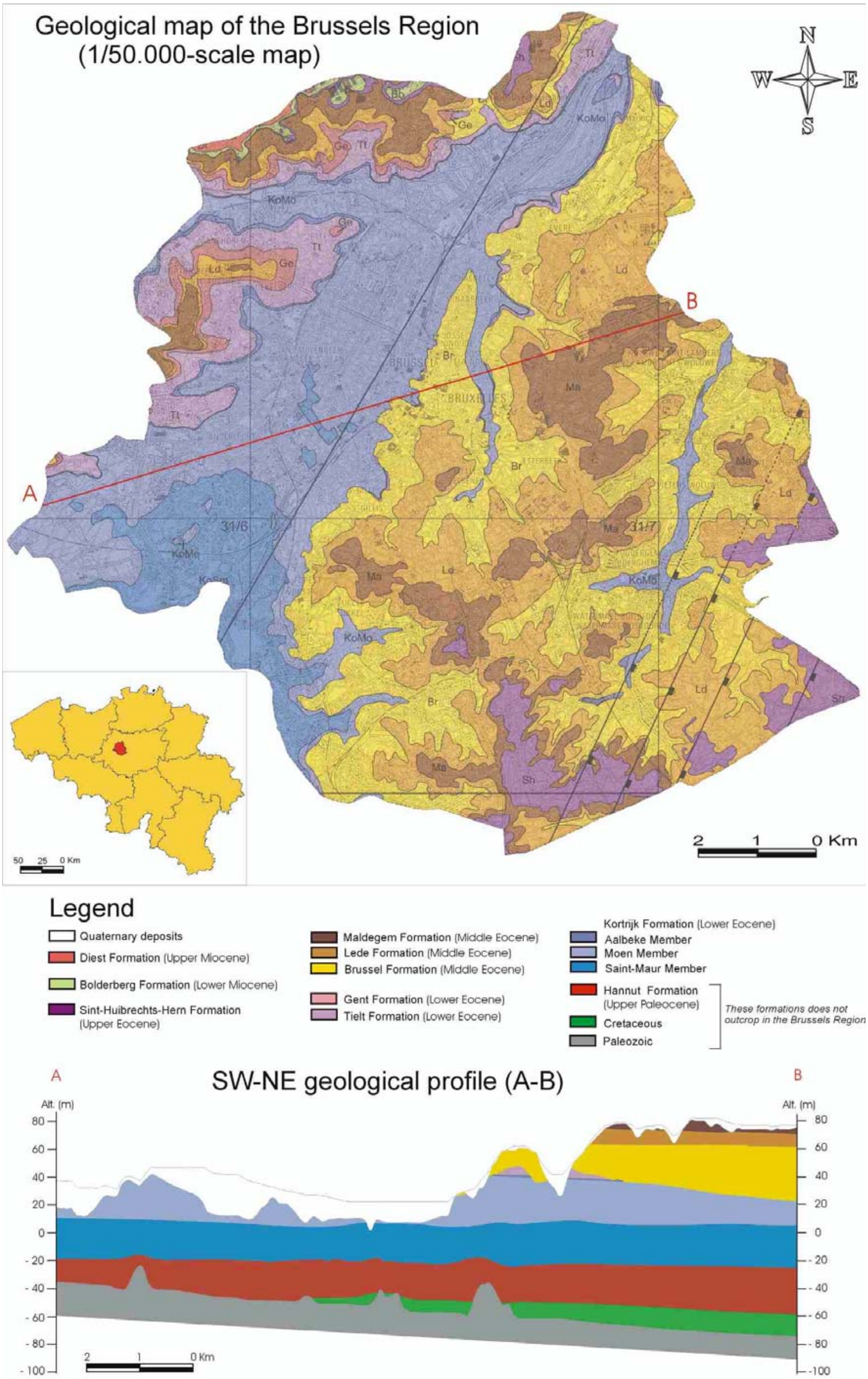

Figure 1. Geological map and profile of the Brussels Region based on the geological map published in 2002.

The Bruxelles Formation (Br, Middle Eocene) is characterised by coarser sands than those of Lede. Calcareous sands occur in the upper part, silicified sands and lenticular sandstones rocks are present in the lower part of the Bruxelles Formation. Generally, this formation is 30-35 m thick but reach a thickness of 70 m in channels structures.

The Gent Formation (Ge, Lower Eocene), subdivided in an upper (Vlierzele) and lower Member (Merelbeke), reaches a thickness of 8 meters. Gent is only observed in the northwestern part of Brussels. The clay and fine sand of the Tielt Formation (Tt, Lower Eocene) are generally 20 m thick. The Kortrijk Formation (Ko, Lower Eocene), subdivided into three Members named successively Aalbeek, Moen and Saint-Maur and is mainly composed of clay (Aalbeek and Saint-Maur) and sand with clay layers (Moen). The average total thickness of the Kortrijk Formation reaches 70 meters. The Upper Paleocene Formation (Hannut, Ha) contains an upper sandy Member (Grandglise) and a lower greenish clay Member (Lincent). The thickness ranges from 15-20 m in the south, up to 28 m in the north. Cretaceous deposits are only present in the northern part of Brussels. White to grey chalk with black cherts from the Gulpen Formation is described only in drill holes. Finally, the basement of Brussels comprises of Paleozoic sandstones, quartzite and slate of lower Cambrian age.

Drill hole data on the territory of Brussels indicates heterogeneous stratigraphic successions with strong lateral thicknesses variations (see profile AB, Figure 1).

GIS AND DATABANK

The in-depth knowledge of the regional and local geology combined with the availability of subsurface data such as a high number of drill holes and Cone Penetration Tests (CPT) makes the ideal area for defining a suitable methodology to create 3D geological models for cities in Belgium. Using ArcGIS desktop software an application has been created with which all the information and available data gathered can be stored in a database and managed within an open, dynamic and visual GIS. Technically, this GIS application is based on the creation of two complementary modules: a relational database management system under Microsoft Access 2000 (Copyright © 1992-1999 Microsoft Corporation) software for the descriptive data and a cartographic management system under ESRI® ArcView 8.3 (Copyright © 1999-2002 ESRI Inc.) software for the geographic raster and vector data.

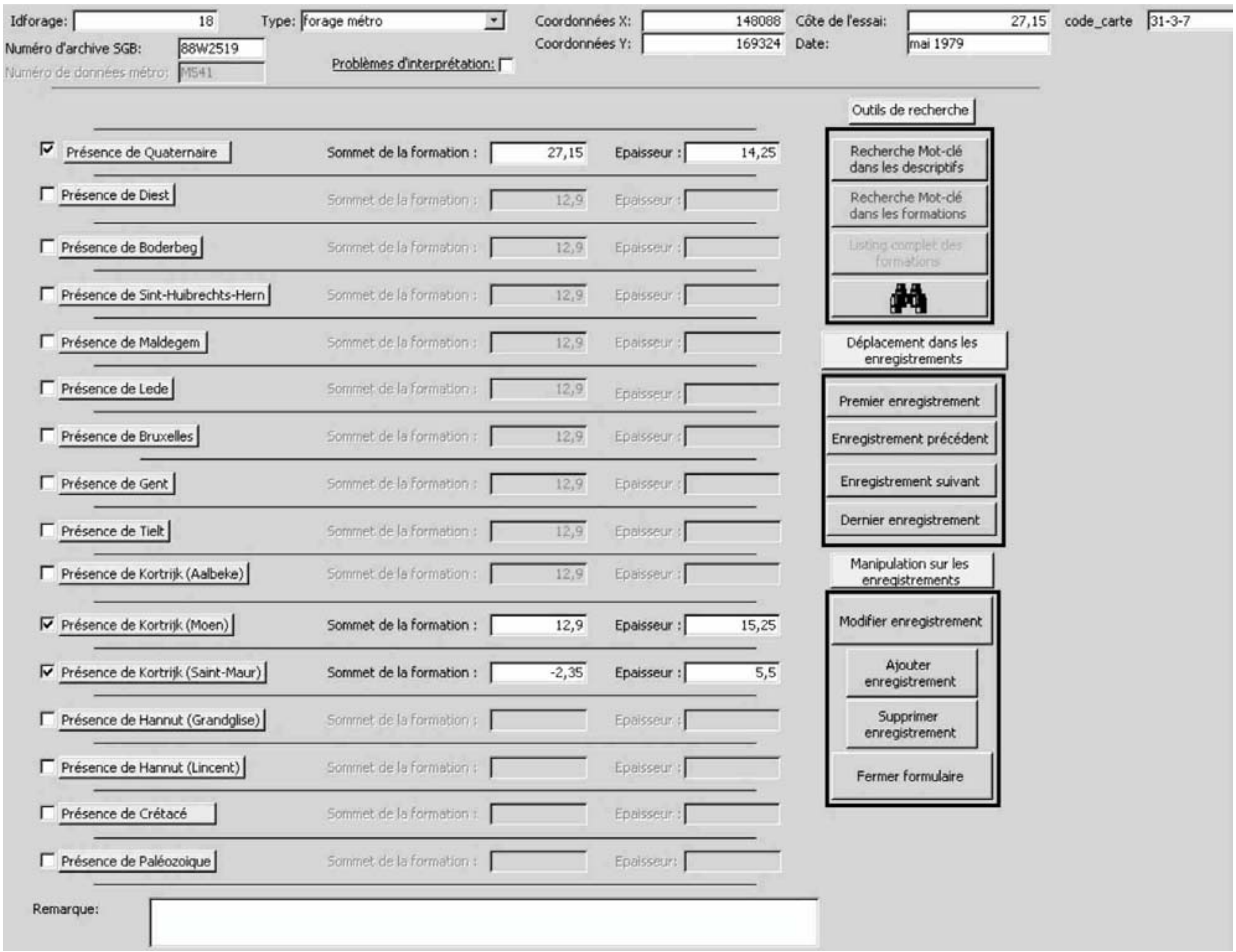

Figure 2. Access 2000 Form view of the drill holes database.

The database and the ArcView software are connected through a geodatabase that avoids double data acquisition and facilitates the management of new information. Drill holes and CPT, constituting the background data and starting point of the program, were stored and managed in the same main database. Data come essentially from two sources:

Firstly, from the Geological Survey of Belgium (GSB) consisting of all the geological information (drill holes, wells, outcrops, underground workings, etc.) gathered by geologists since 1896, the year of inception of the GSB. These geological data concerning the Brussels Region are today almost completely digitised, and therefore available and usable in GIS applications. Secondly, from the archives of the Ministry for the Equipment and Transport of the Walloon Region that since the 1950's collects drill holes and CPT carried out during major building sites (motorways, subway, industrial sites, etc.).

The drill holes collected in the archives for the BUG purposes are not homogeneous in terms of lithological description, information quality and geological interpretations. As a consequence, the most complicated part of the work is to correctly interpret the old descriptions. The next step is to manually input all the data for each drill hole into the database form view (Figure 2) that contains several fields such as X-Y geographic coordinates (Belgian Coordinate System, Lambert 72), altitude (Z in meters), date and type of the drill hole, GSB archive number (primary key), a checkbox when checked indicates that there is a problem in the geological interpretation, the number of the 1:5000 scale topographic map containing the drill hole and a list of the geological formations and members present in the subsurface geology of Brussels. The formation and member names used in the recently published geological map of Brussels (Buffel and Matthijs 2002), correspond to the stratigraphic terms defined by Laga, Louwye and Geets (2001) for the Tertiary in Belgium. These stratigraphic terms are also used in the database. For practical reasons, the Holocene and Pleistocene deposits are included in the term Quaternary. For the same reason, the members of the Maldegem and Gent Formations are not captured in the database because the distinction between these members is not always possible by means of the geological descriptions and not even with the use of CPT information. As a consequence, only 16 stratigraphic geological layers are distinguished and 12 layers have been already created and used to build-up the 3D model. The several formations recognised in the geological description of a drill hole must be checked on in the form view, the Z value (in meters) of the top of a layer must be typed for each checked formation (left centre column, Figure 2) and the thickness would be automatically calculated and indicated for each layer afterwards (right centre column, Figure 2).

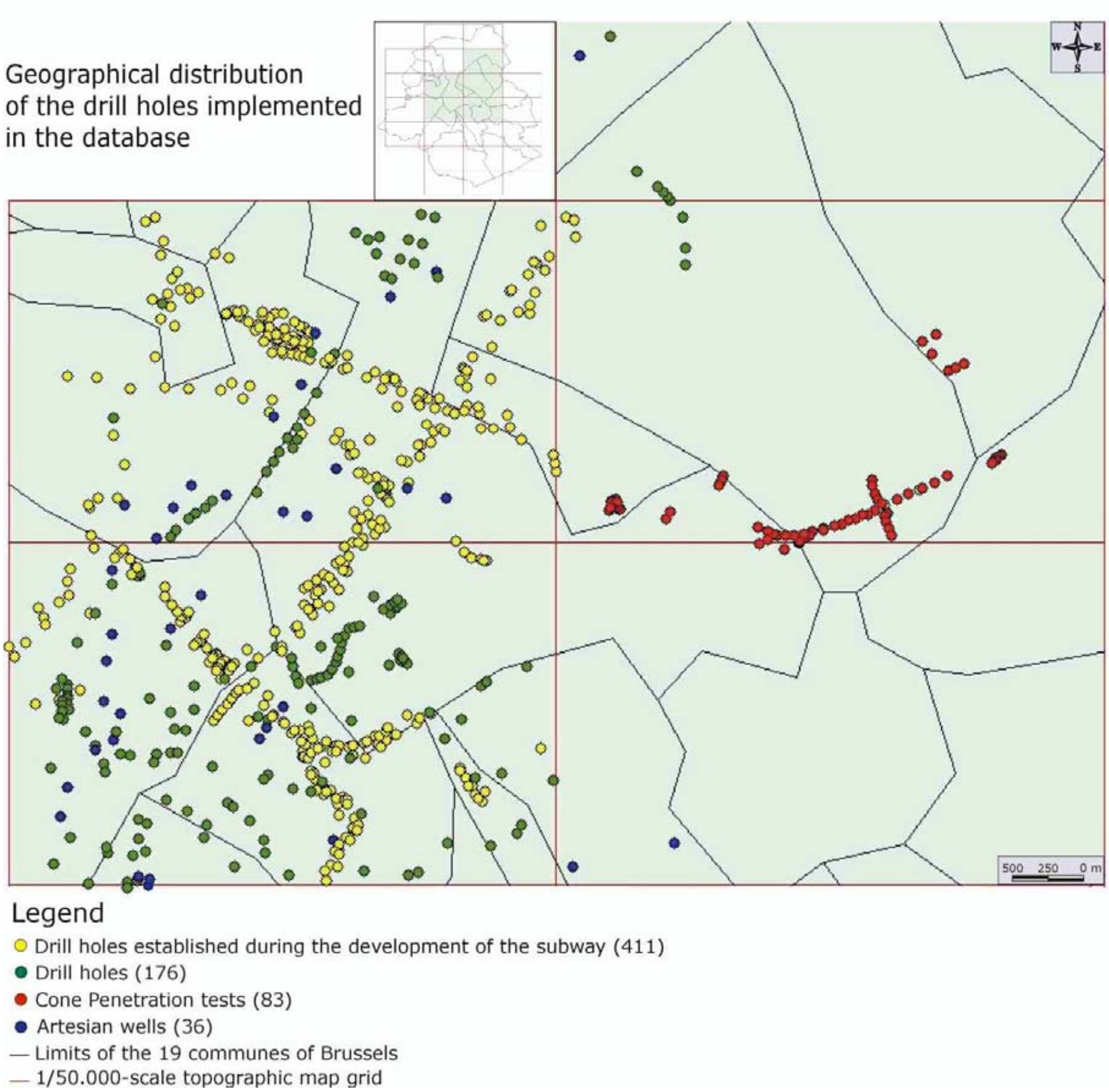

Figure 3. Geographic distribution of the drill holes, wells and Cone Penetration Tests in the centre of Brussels.

To date, more than 700 drill holes and CPT have been used to create the 3D model. The data are distributed on five 1:5000 scale topographic maps that cover an area of 45 km² in the centre of Brussels (Figure 3). The data presented in Figure 3 illustrates the large number of available drill holes present in the left part of the area. This is related to the high density of boreholes drilled during the construction of the subway of Brussels. The right part contains also numerous drill holes that are currently being studied. Unfortunately all the data coming from the CPT must be collected and described, as historically they have not been included in the GSB archives. The step of collecting data outside GSB is highly time-consuming but necessary, as they will drastically increase the amount, the quality and the accuracy of the subsurface geology of Brussels.

The 3D model is developed through the drill holes database. Drill holes are represented in the form of cylindrical columns or sticks of various colours. Each colour corresponds to one different stratigraphic layer. The length of the stick is proportional to the estimated thickness of the geological layer. Once the 3D representation of the drill holes is done, a modelling of the roof of each geological layer is carried out with the Inverse Distance Weighting (IDW) interpolation method using the 3D-Analyst module of ArcView. The 3D model used the drill holes database to generate a set of interpolated geological layers corresponding to the main features in the Brussels area as shown on Figure 4.

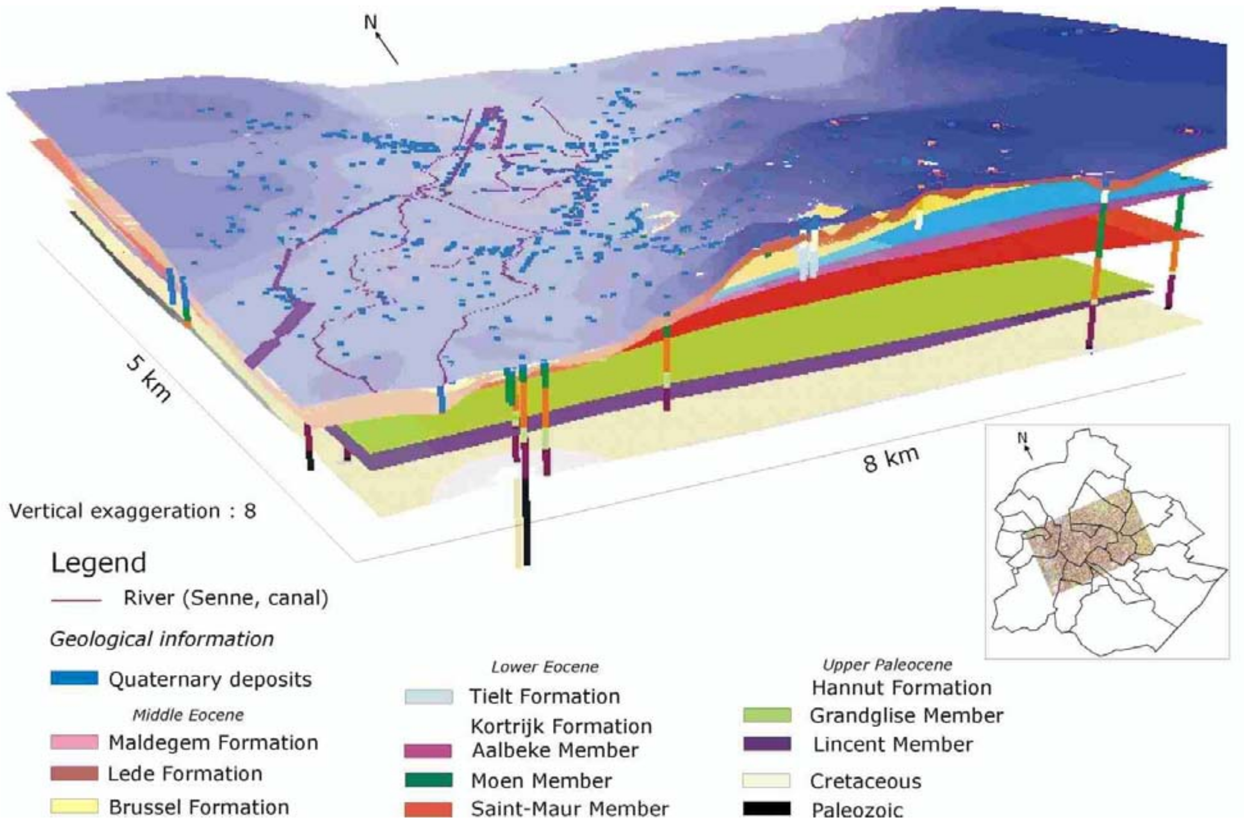

Figure 4. 3D model of the centre of Brussels. The Senne valley is seen just in the centre of the image.

Two other databases have been created in the BUG program. One of them concerns the peat layers observed in the drill holes. The typewritten information in the database contains the X-Y geographic coordinates, the primary key corresponding to the GSB archive number, the nature of the peat layer (peat with sands, clays, loam or peat), and the thicknesses of the layers. Each type of the peat layer is represented by a colour code (as shown on Figure 5) which indicates the presence of different types of organic deposits in the same drill hole such as for example the area close to the Koekelberg basilique (Figure 5) where a peaty loam layer (represented by small blue filled circles) overlies a peat layer (represented by green filled circles). One field of the attributes table links to the file containing the description of the drill hole and by clicking on the point in the ArcMap view this file can be opened. The main purpose is to identify geographically the zones where peaty layers are observed as they could have caused minor ground movements (subsidence) due to water level lowering.

The third database contains the thicknesses of made ground (fill) observed in the drill holes. The IDW interpolation method enables the creation of a contour map of the fill observed in Brussels. The data captured in the fields of this database indicate the X-Y geographic coordinates, the primary key corresponding to the GSB archive number and the thickness of the fill described in the drill holes. Each point or drill hole that contains fill is represented by a colour code related to 6 ranges of thickness between 0 and 24m in the centre of Brussels. The results are illustrated on Figure 6 where the values of the thicknesses of the fills reported for each drill holes have been interpolated using the Inverse Distance Weighting (IDW) method. The interpolated map of man-made deposits, with a highly mixed composition of materials, is of relative importance in urban areas due to possible differential compaction process during building construction phases.

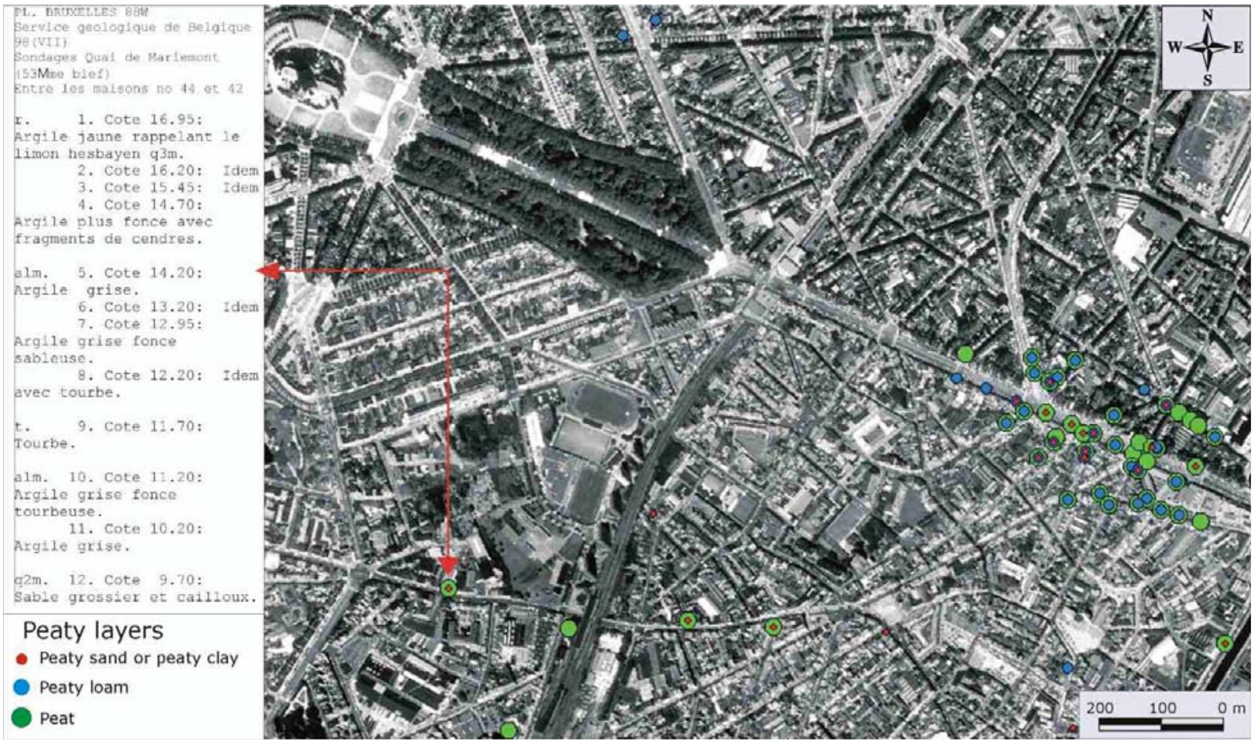

Figure 5. Nature and codification of the peat layers near the Koekelberg basilique (upper left part) and the text file (left side) hyperlinked in the ArcMap view.

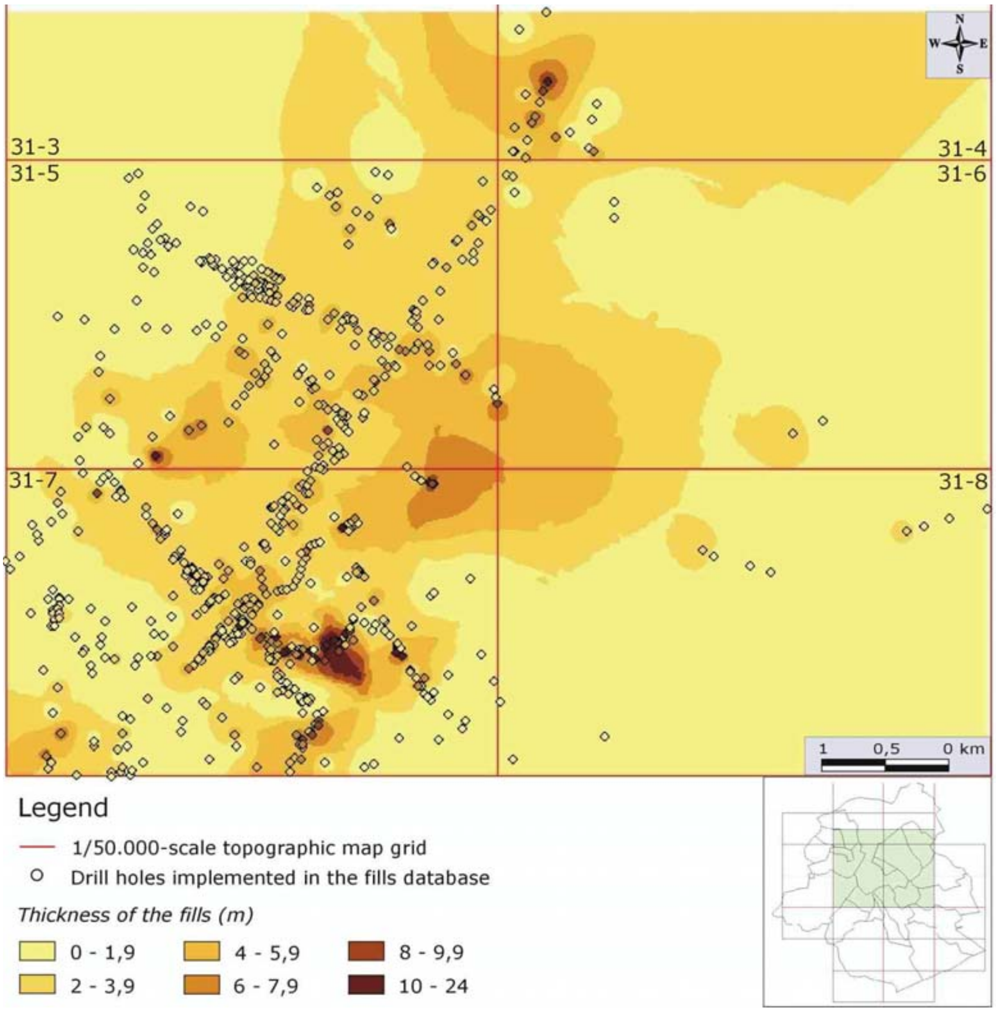

Figure 6. The distribution of made ground in the centre of Brussels is based on the drill hole descriptions and is interpolated using the Inverse Distance Weighting (IDW) method.

GIS APPLICATIONS

A 2D GIS application holds the location of the old underground workings in the Brussels region and provides a decision-support tool for future engineering works such as tunnels or large buildings.

The long history of industrial excavations (quarries, underground workings, etc) in the Brussels area has left artificial deposits beneath much of the urban area. Drill hole descriptions indicate that most of the urban area covers a variable thickness of made ground. Excavations such as quarries and pits range in size from small, shallow "brickfields" (1 to 1.5 m deep) where decalcified loess was collected by hand for local brick making to large (hundreds of meters deep) sand pits. Brickfields are known to exist on most of the plateau in the periphery of the city. Peat layers have been exploited in the past in the Maelbeek, Schaerbeek and Woluwe valleys of Brussels. Sands, mostly from the Bruxelles Formation, were exploited in numerous sand pits. Since the beginning of the 19h century, the rapid development of the urbanisation in Brussels has caused an increasing need of sand. This evolution has led to the enlargement of the sand pits and to increased surface exploitation..

Sandy limestones are described in the lower part of the Lede Formation. These stratified beds, generally ranging in thickness between 10 cm and 40 cm and in some places up to 1 m, have been intensively exploited as building stones on top of the hills surrounding the old historical centre of Brussels since the Middle Ages (Camerman 1955a). It seems that the activity in underground workings seized at the end of the 18th century. Ten communes of Brussels (Bruxelles, Schaerbeek, Evere, Woluwe-Saint-Lambert, Woluwe-Saint-Pierre, Etterbeek, Auderghem, Ixelles, Saint-Gilles, Forest) are effected by these underground workings as shown on Figure 7.

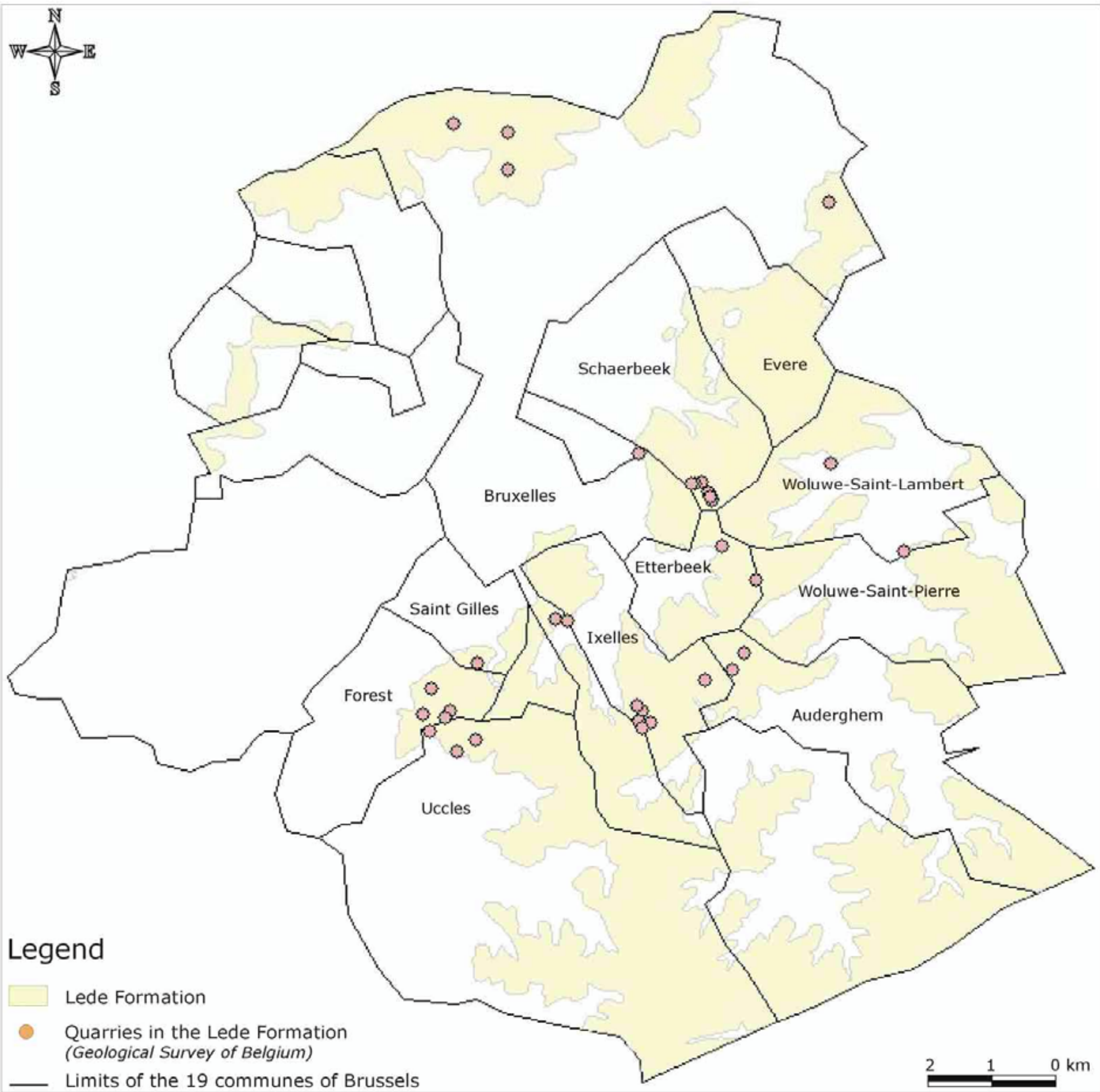

Figure 7. Coverage of the Lede Formation (yellow) based on the geological map. The light brown circles represent all places where underground workings have been identified and described in the GSB archives.

These exploitations are mainly known through old manuscripts and sometimes are discovered during the construction of large buildings in these communes such as the shafts, galleries and cavities found in Ixelles on the site of the Free University of Brussels (Camerman 1955b). Until now, we have created an inventory of more than 33 places where cavities, galleries, shafts or a combination of these structures, have been observed and described.

CONCLUSIONS

By using a 3D model tool to visualise more precisely the geology of a city, we intend to make geological information more accessible to a wider audience of users, such as engineers and decision-makers who can use the geological information to better predict, plan and manage the impacts caused by the developments of new infrastructure on the territory of Brussels. This is particularly true for the regional express railways network that will be developed during the next five years. These railway lines will connect cities located at distances higher than 20 km of Brussels both in Flanders and in Wallonnia. Major engineering works (tunnels, to put four-lane in place of the existing two-lane railway lines) will be necessary to improve the current network.

The next stages of the project will be:

- to improve the current model through the integration of all the data (drill holes, cone penetration tests) collected and gathered elsewhere;
- to implement in the GIS application the location of all the data dealing with the underground workings and quarries related to the Lede Formation;
- to decipher and analyze fluid/sediment migration pathways and associated drainage areas. The potential sediment migration pathways are defined by down-dip geometric fluid or material flow lines that are initiated from a source point and follow the steepest geometric route within a geological unit. The flow lines terminate at local deposition centres with the lowest altitude values. This is particularly important considering the climatic fluctuations and the recent inundations combined with the increasing frequency of these kind of hazardous climatic events observed during the last decades in some parts of Brussels.

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