Z. Dt. Ges. Geowiss. (German J. Geol.), **167 (4)**, p. 377–388, 7 figs., 1 table **Article**

3D GIS-based visualisation of geological, hydrogeological, hydrogeochemical and geothermal models

Mar Alcaraz[1,2], Enric Vázquez-Suñé[3,4], Violeta Velasco[3,4] & Marc Diviu[3,4]*

Alcaraz, M., Vázquez-Suñé, E., Velasco, V. & Diviu, M. (2016): 3D GIS-based visualisation of geological, hydrogeological, hydrogeochemical and geothermal models. – Z. Dt. Ges. Geowiss., 167: 377–388, Stuttgart.

Abstract: An integrated methodology is proposed for the 3D visualisation of underground resources related to groundwater. A set of tools named HEROS3D was developed in a GIS environment to support the generation of 3D entities representing geological, hydrogeological, hydrochemical and geothermal features. It uses a geospatial database in which hard data and interpreted data are stored. The interpretation of geological data can be visualised in 3D as surfaces or fence diagrams, and as 3D representations of boreholes. Moreover, HEROS3D allows editing geological surfaces by several methods, getting involved in the 3D geological modelling. Along with the geological model, HEROS3D generates 3D visualisation of chemical values and piezometric levels, whose temporal evolution can be taken into account. In addition, three-dimensional representations of thermal plumes generated by the exploitation of shallow geothermal energy can be created and visualised jointly. In this way, all steps in hydrogeological modelling can be visualised in three-dimensional space, to facilitate understanding and validation of the model. Results are shown for a case study in Barcelona, Spain.

Keywords: 3D data integration, 3D geological models, 3D groundwater models, GIS

1. Introduction

Groundwater, with increasing frequency, is considered a key factor in water management of urban areas (Lerner 1996, Howard & Israfilov 2002). It is a heavily exploited resource, which supports different types of anthropogenic pressure. For instance, intensive pumping of groundwater (water supply, industry, etc.) can produce a number of undesirable consequences such as surface settlements or the deterioration of the quality of groundwater due to different processes (Vazquez-Suñe et al. 2005, Jurado et al. 2012). When groundwater extractions tend to be reduced or abandoned due to pollution or changes in land use (e.g. relocation of industries), groundwater levels recover, creating flooding and damage to building foundations and other underground civil infrastructures as services (telecom, gas, electricity or water) or transport networks tunnels (Font-Capo et al. 2011, Pujades et al. 2012, Attard et al. 2015).

Moreover, in recent years, a new factor of pressure has been added, namely the exploitation of shallow geothermal energy (SGE). SGE is a renewable energy resource based on the extraction or dissipation of thermal energy in the first approx. 100 m depth. Due to the rapid growth in the implementation of SGE exploitations, incipient thermal impacts are affecting current users of SGE because of the scarcity of management methodologies for this energy resource (Hähnlein et al. 2013, García-Gil et al. 2015).

To accomplish a thorough analysis and management of urban underground resources, especially of SGE and others, it is mandatory to improve the knowledge of groundwater flow processes to define the behaviour and predict the response to different environmental stresses (Lo Russo & Civita 2009, Wagner et al. 2013). The efficiency and proper performance of underground services, such as dewatering systems or SGE exploitations, depend largely on the properties and conditions of the groundwater system (Capozza et al. 2013, Angelotti et al. 2014). Only by knowing the groundwater behaviour, an efficient management of this complex system would be guaranteed by groundwater modelling.

Hydrogeological models represent an essential tool to identify, conceptualise and quantify the different processes that occur in the subterranean media and allow evaluation of

---

*Addresses of the authors: [1]Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Av. Rivadavia 1917, C1066AAJ Ciudad Autónoma de Buenos Aires, Argentina; [2]Instituto de Hidrología de Llanuras "Dr. Eduardo J. Usunoff", Av. República Italia, 780. C.C. 47 (B7300) Azul, Provincia de Buenos Aires, Argentina; [3]Institute of Environmental Assessment and Water Research (IDÆA), CSIC, Jordi Girona 18–34, 08034 Barcelona, Spain; [4]Associated Unit: Hydrogeology Group (UPC-CSIC) / malcaraz@faa.unicen.edu.ar.

www.schweizerbart.de
DOI: 10.1127/zdgg/2016/0093
1860-1804/0093 $ 5.40

affections and interferences (Vázquez-Suñé et al. 2005, Tait et al. 2004, Schirmer et al. 2013). The construction of reliable hydrogeological conceptual models requires a solid geological characterisation of the subsurface media (e.g. Ross et al. 2005, Velasco et al. 2012b). Both the geometry and properties of the different geological bodies and their connectivity must be provided with an adequate scale. Moreover, according to the nature of the process of interest (e.g. geotechnical, hydraulic or geothermal problems), the definition of specific variables will be required.

3D analysis and visualisation of geological models are required to understand and represent the heterogeneity of the aquifers in the three dimensions of the space (Koller et al. 1995, Tame et al. 2013, Turner et al. 2014). In fact, nowadays 3D geological modelling is not a goal, but a step in hydrogeological projects. Besides, the 3D visualisation of geological models and hydrogeological conceptual models, including the impacts produced by the exploitation of subterranean resources, can help to define and establish particular management strategies. Several authors have used 3D visualisation of geological and hydrogeological models to face different situations as geotechnical problems (De Rienzo et al. 2008), hydrochemical problems related to gypsum dissolution conditions (Thierry et al. 2009) and groundwater management (Gill et al. 2011).

However, existing methodologies have been not designed to deal with some specifics aspects related to a comprehensive analysis and assessment of the groundwater system nor the analysis and visualisation of specific impacts on this environment in a three-dimensional environment. To deal with this situation, some hydrogeological methodologies and software have been developed. For instance, GVS (Cox et al. 2013) is a stand-alone application oriented to visualise 3D geological (cross-section and surfaces) and hydrogeological data in a friendly user interface, including tools to query and visualise temporal evolution of hydrogeological variables. In spite of these advantages, previous geological and hydrogeological conceptual models must be carried out outside this platform, thus it needs of additional software for pre-processing of hydrogeological data. Strassberg et al. (2010) developed a set of tools in a GIS environment (Arc Hydro Groundwater Tools) that support the creation and the storage of 3D objects such as hydrostratigraphy, cross-sections and volumetric objects. In addition, this platform includes a set of tools to facilitate the generation of 2D/3D modelling elements and its database structure enables the generation of SQL queries to map time series. Additionally, Chesnaux et al. (2011) present an effective methodology to build a comprehensive database through the combination of a Relational Database Management System (RDBMS) that incorporates instruments for data quality control and the aforementioned Arc Hydro Groundwater Tools. These platforms and methodologies allow the integration of the main hydrogeological characteristics, such as geological and hydrogeochemical models, but do not include other more specific characteristics, such as those related with the geothermal behaviour of groundwater when SGE is been exploited.

Nevertheless, further procedures may be improved during construction of 3D geological models, especially for the management, visualisation, retrieval and understanding of detailed geological and hydrogeological data and parameterisation in a 3D GIS environment (Turner 2006). Some relevant aspects must be taken into account related to data management and visualisation in a GIS environment. For instance, facilitating the creation and modification of geological surfaces or integrating the visualisation of all the available hydrogeological data in an understandable manner. Once the media is properly characterised and an exhaustive geological, hydrogeological, hydrogeochemical and geothermal analysis has been carried out, the expected impacts obtained from these analyses should be available.

In this situation, this paper presents a methodology that aims to integrate in a unique 3D GIS environment the whole process of hydrogeological modelling with 3D capabilities, by focusing on (1) the development of 3D geological models suitable for hydrogeological modelling and (2) the 3D validation and visualisation of geological, hydrogeological, hydrogeochemical and geothermal models. Both aspects are accomplished with a single software package that is presented here, named HEROS3D, with no need for conversion or exchange between different platforms.

2. Study area and hydrogeological settings

The HEROS3D toolset was used in a case study involving an urban aquifer to illustrate its performance. The study area, named La Sagrera, is located in a highly urbanised area in Barcelona, on the Mediterranean coast in northeast Spain (Fig. 1). It is framed around the civil works related to the construction of the Sagrera-Meridiana Intermodal Transportation Hub, which will receive passengers of high speed and suburban trains, subway and buses. Its deepest base reaches -6 m a.s.l. and is located below groundwater level.

Geologically, the study area of La Sagrera is mainly characterised by the presence of Quaternary succession of the Besòs Delta that rest unconformably over a substratum of Palaeozoic rocks. The main features of the geological units in this area are summarised in Table 1 (Velasco et al. 2012a). The geospatial database HYDOR includes 87 points with lithological descriptions that were interpreted with HEROS to define contact points for each of the nine hydrogeological units defined (Table 1). 2061 hydrogeochemical data of 239 chemical compounds are also available from 138 groundwater points, from which 29 points have geological descriptions. Finally, 1368 piezometric measurements are also stored for the groundwater points.

A comprehensive geological analysis was carried out in Vázquez-Suñé et al. (2016) that comprises the complete geological methodology proposed of feedback and validation. Here, only the methodologies and output of HEROS3D are shown.

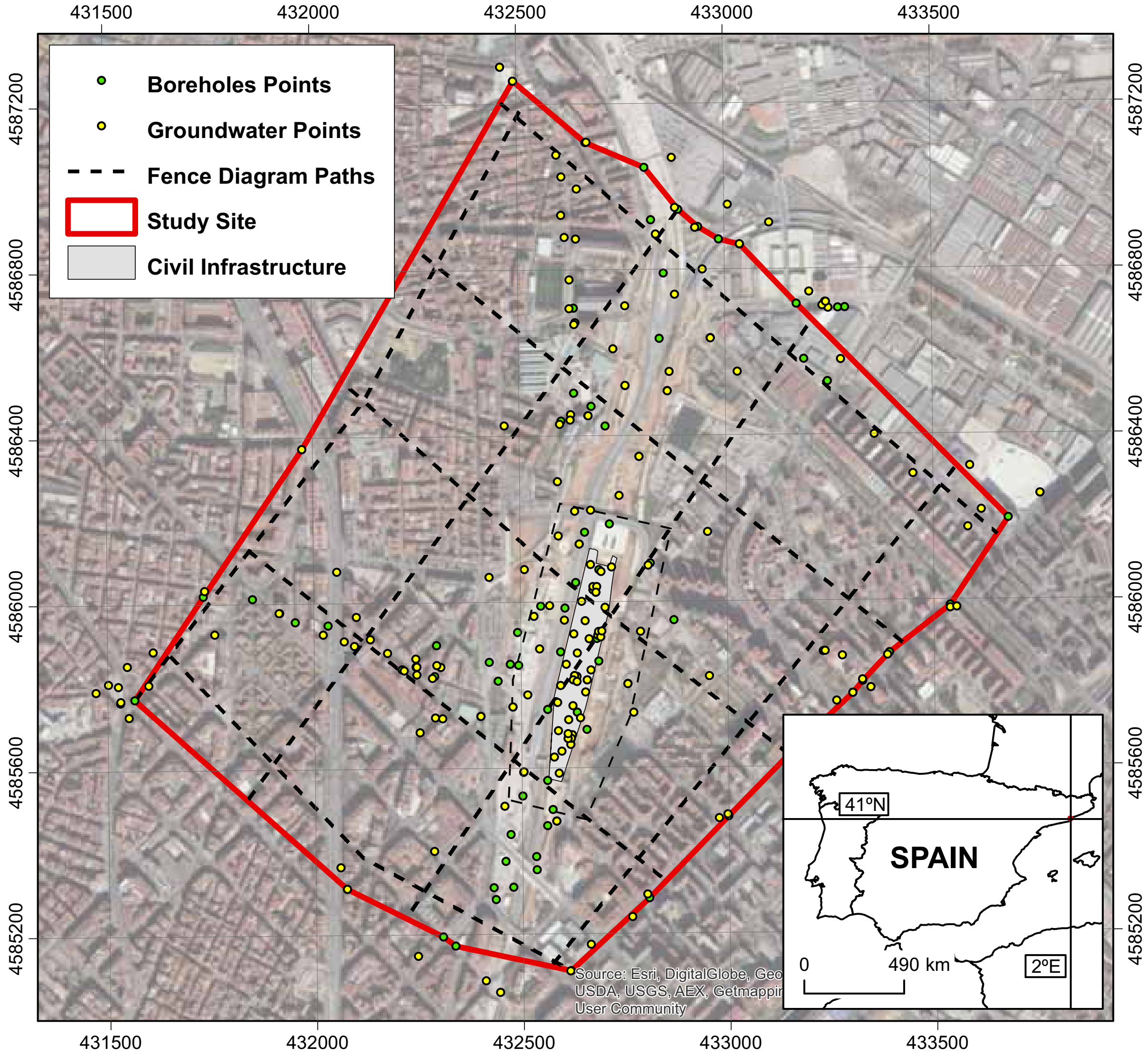

Fig. 1: Location map of the study area along with groundwater points, geological points and path lines for fence diagrams. Orthograph of the study area; UTM, ED-50, 31N. Basemap provided by ESRI (Imagery: http://goto.arcgisonline.com/maps/World_Imagery).

Table 1: Lithological, hydrogeological and chronological description of the different geological units of the study area.

Age	Unit	Lithological description	Hydrogeological description
Post-glacial – Holocene	F2	Local heterometric and massive deposits of clast supported and very coarse-gravels with clay-sandy matrix into high series of lutitic units with some sandstone beds	Partially permeable (permeable in areas with less silt)
	F1		Less permeable (only permeable in areas with less silt and clay)
	E	Well sorted gravels and sandstones	Aquifer
	D	Coarse-grained facies belt made up by sands and gravels	Aquitard
	C2	Well rounded to angular clast supported pebbles with sand	Aquifer
	C1	Poorly sorted gravels, occasionally with sandy matrix and some lenses of organic matter	Partially permeable (permeable in areas with less silt)
Pleistocene	B	Massive lutites with isolated poorly sorted gravels and pebbles, which are passing to interlayered sandstones and clays	Less permeable (only permeable in areas with less silt and clay
	A	Poorly sorted gravels, occasionally with sandy matrix and some lenses of organic matter	Aquifer
Pliocene/ Palaeozoic	Substratum	Grey marls in some places interbedded with sandstones and gravels / Granite	Less permeable (only permeable in areas with less silt and clay or in fractured areas)

3. Methodology for 3D integration of data

The proposed methodologies aim to analyse, visualise and integrate in the three-dimensional space the variables and properties required to define a comprehensive hydrogeological model. This is possible because it is embedded in a wider hydrogeological platform, named HEROINE, which includes facilities to perform a complete hydrogeological analysis in a single GIS environment. The software platform HEROINE facilitates a detailed hydrogeological conceptual modelling by means of a geospatial database (HYDOR) and several sets of GIS-based analysis tools developed in a two-dimensional environment, as extensions of ArcMap (ArcGIS; ESRI). They are accessible by different toolbars. These toolsets manage the geological (HEROS toolset), hydrogeological (HYYH toolset), hydrochemical (QUIMET toolset) and shallow geothermal (MetroGeother toolset) data stored in HYDOR geodatabase (Fig. 2). These instruments are described in more detail in Velasco et al. (2012b), Velasco et al. (2014), Criollo et al. (2016) and Alcaraz et al. (2016). To give three-dimensionality to all these data types, a set of tools is presented named HEROS3D. It allows for 3D geological and hydrogeological analysis. This set of 3D analysis tools is accessible through a toolbar in ArcScene, the 3D environment of ArcGIS 10.0 (ESRI) software package.

3.1 3D Geospatial data storage: HYDOR geodatabase

The HYDOR geospatial database follows the Personal Geodatabase structure provided by ArcGIS (ESRI). It is composed of different datasets that include a variety of key spatial and non-spatial data necessary for a complete geological and hydrogeological study. The main components include geological, hydrological, hydrogeological, hydrochemical, geophysical and geothermal features. This geodatabase allows storing an accurate and very detailed geological description (e.g. lithology, fossils contents, geotechnical properties, etc.) that can be generalised and up-scaled. In order to ensure the standardisation and the harmonisation of the data, several code lists (e.g. list of lithology, fossils, age ...) were created taking into account standard guidelines such us One Geology (OneGeology 2013), OGC WaterML (OGC 2012) and INSPIRE (INSPIRE 2011, 2013).

In addition, the geometry and attributes of the different interpretations derived from the data placed in the database are also stored separately to allow additional interpretation and to act as a framework for a new project. This information related to the interpretation of the geological description for each borehole must be available in the geodatabase. This implies a pre-process of the data by the user. The HEROS toolset allows the users to apply advanced techniques of interpretation to integrate all available information, such as stratigraphical analysis. Up to two different levels of interpretation can be stored as hydrogeological units and subunits. This interpretation will be queried to represent it in 3D in several forms by HEROS3D tools.

3.2 3D Geological data management

Two common situations are usually found related to geological models in groundwater modelling. On one hand, it is common to find simplistic approximations of real aquifer geometry and spatial variability of geological and hydrogeological properties that show the lack of geological knowledge of the study site. Usually, this is because there are not

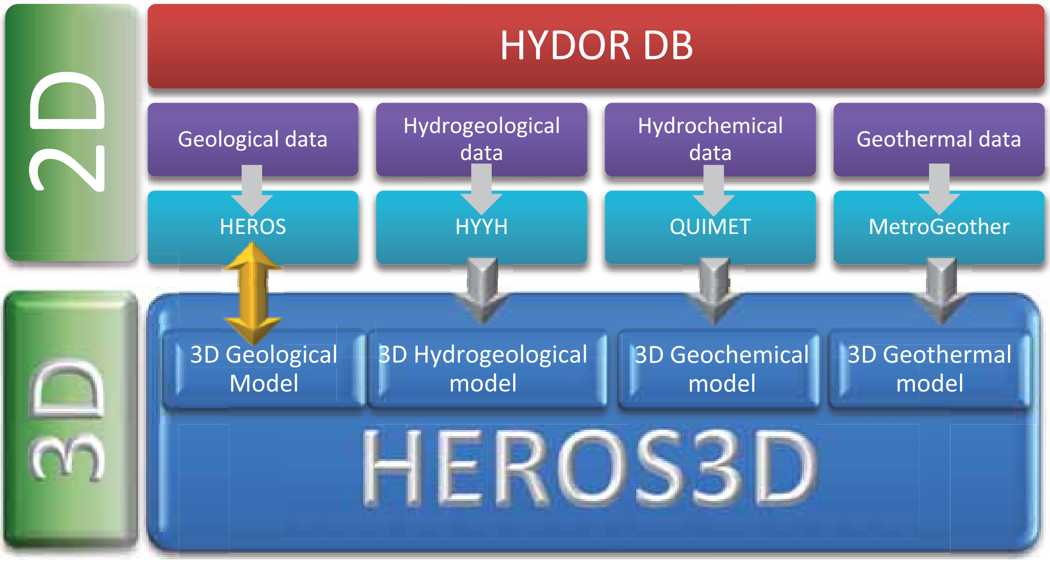

Fig. 2: Schematic view of the HEROINE platform. HEROS3D provides of 3D visualisation for the different data models stored in the HYDOR database. Each one of these models defines a particular aspect of the hydrogeological conceptual model.

enough resources (time or funds) to obtain the detailed input geological data from drilling, geophysics, etc. (Wycisk et al. 2009). On the other hand, there are studies where more complex geometries are defined for the geological structures such as detailed characterisations of faults and folds. These complex geometries do not fit to the multilayer character of most common software for hydrogeological numerical modelling, such as Feflow (Trefry & Muffels 2007), Modflow (McDonald & Harbaugh 2003) or Visual Transin (GHS-UPC 2003). This implies a post-processing of the geological model to adapt the geometry to hydrogeological modelling process and then importing a multi-layered geological geometry to hydrogeological numerical software.

For groundwater, the layered structure of the system justifies the application of semi-3D GIS platforms. For instance, it is common to encounter a disposition of at least two aquifers, one deep and one shallow. The impacts on each of them together with the interrelation between them can only be represented simultaneously in 3D. However, these standard multi-layered systems are quite limited for modelling, visualising, and editing subsurface data and geologic objects and their attributes. Here, a methodology for improving the modelling of multi-layered systems is proposed.

As stated above, HEROS is the set of instruments in the HEROINE platform oriented to lithological and stratigraphic analysis. The HEROS toolset allows us to work with 3D geological data in a bi-dimensional space and consists of two subcomponents: (1) Borehole Diagram tools (BHD) and (2) Stratigraphic Cross-Sections Correlation tools (SC-SC). BHD tools allow visualising the lithological information for each borehole from the database in order to define its geological and hydrogeological units and subunits. The interpretation generated is also stored in the database, so they can be further visualised and reinterpreted.

To merge these individual interpretations in an integrated regional hydrogeological model, SC-SC tools allow the generation of geological profiles that display the lithological columns of the boreholes together with the defined geological and hydrogeological units/subunits and the graphical results of in situ tests (e.g. diagraphy). Complementary information such as the surface terrain profile extracted from the DEM and the representation of the geological outcrops over this profile is shown. It is also possible to visualise in the same environment the profiles of those geological surfaces that have been previously interpreted. Furthermore, other information such as the distance between the boreholes, the depth to each stratum, the visualisation of seismic profiles on other images (such as previous interpreted geological profiles) is also included in the resulting cross-sections. From the graphical representation of all this information, the geologist is able to define and construct a coherent geological model that serves as basis for a hydrogeological model.

These geological sections, besides representing the data stored in the database, create a bi-dimensional canvas that supports drawing the geometry of the conceptual model defined by the geologist. The user defines the contact layer between geological units, and also faults and other discontinuities, as lines. The data created inside SC-SC canvas can be exported as three-dimensional data. Not only is the 3D geometry established, but attributes related to these lines are also created, such as unit name, top and bottom units and other alphanumeric information.

After the geological analysis in the two-dimensional space with HEROS tools, the geological interpretation is available in HYDOR and ready to be queried by HEROS3D. HEROS3D extends the functionality of HEROS to work in the three-dimensional space. These analysis instruments cover a wide range of methodologies for visualising, querying and interpreting geological data in a 3D environment. They include, among others, different commands that enable the user to: (1) query and visualise in 3D the different units/subunits interpreted for each borehole (Borehole Tubes); (2) create 3D surfaces (TINs) automatically for the specific units/subunits interpreted from the boreholes and recorded in the database; (3) perform further calculations with the aforementioned 3D surfaces (e.g. extension); (4) create automatically fence diagrams. These facilities and others are explained below.

3.2.1 Borehole Tubes

The borehole data interpreted previously with HEROS as unit or subunits and stored in the geodatabase HYDOR is only visible in three ways: (1) in raw format inside the geodatabase table; (2) in 2D individually with BHE tools or (3) jointly with related boreholes in cross-sections with SC-SC tools from the HEROS toolset.

HEROS3D creates Borehole Tubes entities, which are 3D visualisations of the borehole stored in HYDOR geodatabase. The Borehole Tubes represent the geological interpretation defined previously for the boreholes, such as geological or hydrogeological units or subunits. These representations allow understanding the location of geological units and subunits in the three-dimensional space as an additional information layer, which can be displayed jointly with further information.

A Borehole Tube entity is composed of several coloured cylinders, each one representing a defined geological unit or subunit lot. Its diameter can be adjusted to the scale of the model to make it visually compatible with other data. The Boreholes Tubes that represent the 3D visualisation of geological interpretations for La Sagrera are shown in Fig. 3.

3.2.2 Geological surfaces

HEROS3D toolset expresses its maximum strength and capabilities when managing geological surfaces. It allows the user to create automatically the surfaces from the geological data stored in HYDOR and to modify them following different processes described below.

3.2.2.1 Automatic creation of geological surfaces

HEROS3D generates automatically the surfaces of the selected geological units or subunits stored in the geodatabase HYDOR. A Triangular Irregular Network (TIN) surface re-

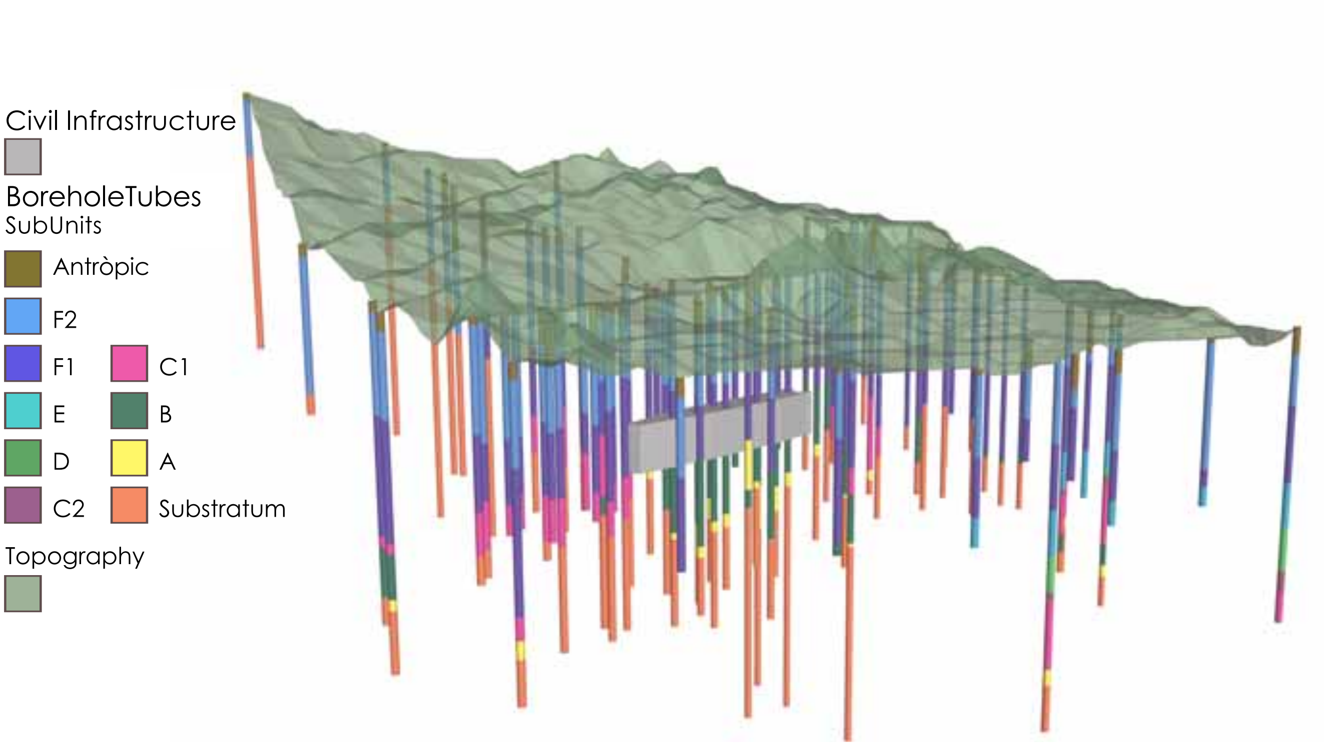

Fig. 3: Boreholes tubes entities for the study area. The topography is shown in green along with the piezometric surface and the main 3D structure of Sagrera-Meridiana station. Infrastructure: 566 metres long. Vertical exaggeration factor: 15.

presenting the bottom of the specified interpretation unit is added to the display. It is created as a linear interpolation from the punctual interpretation data of each unit or subunit stored in the geodatabase. These surfaces can represent the first simplified version of the 3D geological model. They can also be used in the iterative process during the definition of the 3D geological model with HEROS because their intersection can be visualised in cross-sections created with SC-SC tools to contribute with additional interpolated information where boreholes are sparse.

These surfaces can be modified by adding particular 3D data generated in ArcScene with its inherent tools or with SC-SC tools to develop the final version of the 3D geological model.

3.2.2.2 Modification of existing geological surfaces by extension

Usually, the boundaries of geological and hydrogeological models are not properly defined because the scarcity of data in the margins is common. To overcome this problem, a set of instruments was created. It enables the user to extend the interpreted geological boundaries of the model by using three-dimensional extrapolation techniques. It is based on the extension of the surfaces created previously (or whatever surface saved as TIN) to cover the entire domain. This extension can be calculated by extending up to a specific distance to the borderline of the surface. New triangles are generated and added to the existing TIN. The slope of these triangles can be defined by the modeller in two ways: (1) maintaining the slope of the triangles located in the actual boundary or (2) defining a constant value as slope.

A polygon representing the entire domain of the geological or hydrogeological model can be used as a clip to delimit these extended surfaces and adjust them to the model boundary.

3.2.2.3 Modification of existing geological surfaces by intersection

In order to be able to use the defined 3D geological surfaces generated in further processes of hydrogeological and geological modelling, they must be topologically valid. This means that in 3D meshes, edges and nodes of the intersecting surfaces must be watertight. To date, these geometric problems associated with the intersection of 3D geological surfaces are not solved by using the default techniques offered by the inherent capabilities of ArcGIS. To overcome this, HEROS3D enables the user to obtain the 3D intersection line between two intersecting surfaces. Inherent ArcGIS tools can be then used to create the boundary of the surface of interest with this 3D line and clip the geological surface. This methodology is based in the triangle-to-triangle intersection algorithm proposed by Tropp et al. (2006). The geological surfaces generated automatically for La Sagrera are shown in Fig. 4. Most of them were extended up to the boundary of the model or up to their intersection with other surfaces.

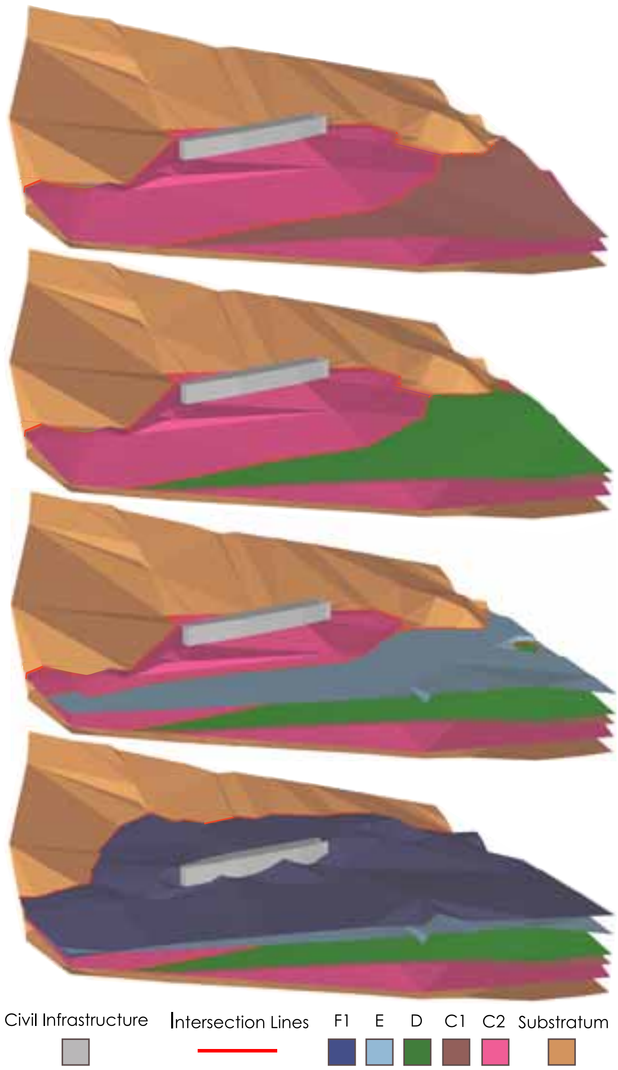

Fig. 4: Intersection of contact surfaces for geological units interpreted for the study area. Infrastructure: 566 metres long. Vertical exaggeration factor: 15.

3.2.2.4 Validation and feedback between interpreted geological surfaces and HYDOR geodatabase

To improve the geological modelling process, the information generated during the interpretation can be reintroduced in previous steps to validate, edit and correct, when necessary, the interpreted geological surfaces. In this way, successive versions of the 3D geological model can be generated, stored and reused for reinterpretation. For instance, the 3D geological surfaces constituting the geological model can be visualised in the geological cross-section to check the consistency among all existing data. Additionally, the final 3D geological model can be stored in the geodatabase as depth values of each 3D surface for specific control points.

3.2.3 Fence diagrams

To disseminate 3D geological models and make them accessible and easily understandable, it is common to visualise them through fence diagrams. The fence diagrams are vertical sections of geological units following specific lines over the domain. HEROS3D allows them to be created automatically from a geological surface defined previously by the modeller, e.g. the TIN surfaces generated automatically in the previous step. These surfaces must represent the bottom of the geological units. The lines that define the path of these vertical sections must be available as geometrical entities.

Once the geological surfaces are available for La Sagrera (Fig. 4), the fence diagrams can be generated automatically following the paths of Fig. 1 for this study site, as shown in Fig. 5. This technique supposes an advance in the automatic generation of fence diagrams. Alternatively, the fence diagrams can also be obtained by exporting to 3D each of the different units/subunits drawn as 2D polygons in each geological profile generated with HEROS. HEROS3D allows the creation of fence diagrams directly on a 3D environment from existing geological surfaces automatically.

3.3 3D and temporal hydrogeological data management: Piezo Tubes

The hydrogeological data can be analysed in the same platform with HYYH (Criollo et al. 2016). These tools query the hydrogeological data stored in HYDOR such as groundwater levels registered over a period. HEROS3D represents in the three-dimensional space the temporal evolution of the groundwater table registered from field campaigns. A tube representing the groundwater level can be visualised whose diameter can be modified by the modeller to make it compatible with the additional geological or hydrochemical information. The base of this tube starts on the bottom surface of the hydrogeological unit that is being studied, and reaches the groundwater head. This tube can vary over time if a temporal evolution of the groundwater level has been registered.

Temporal evolution of piezometric values for groundwater points was created for the study site of La Sagrera. Fig. 6 contains the Piezo Tubes, which reflect the piezometric level variations for each groundwater point.

3.4 3D and temporal hydrogeochemical data management

The hydrochemical query module in 2D is named QUIMET (Velasco et al. 2014) and allows for different interpretation techniques in 2D of hydrochemical data stored in HYDOR, such as the creation of Piper, Schoeller-Berkaloff, SAR of Stiff diagrams. Moreover, the time can be considered also as the fourth dimension. Temporal evolution graphs of the concentration of parameters can be generated. However, it is limited to a bi-dimensional analysis. HEROS3D gives three-

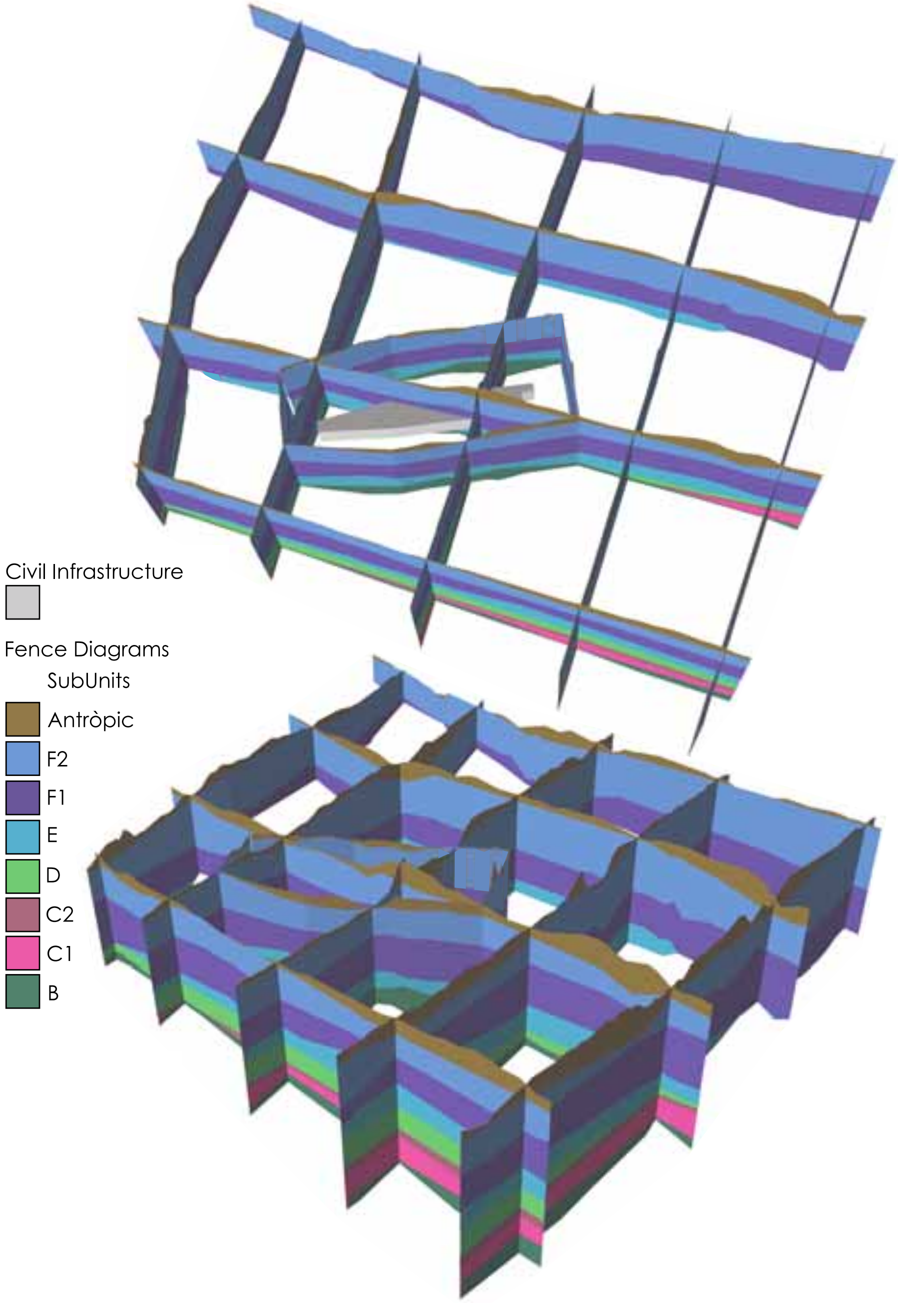

Fig. 5: Fence diagrams for geological model of the study area. Infrastructure: 566 metres long. Vertical exaggeration factor: 10.

dimensionality to QUIMET. Once the hydrochemical analysis has been carried out in QUIMET, the results can be visualised with HEROS3D.

3.4.1 Chem Tubes

The well is represented as a cylinder inside the hydrogeological unit where the water sample has been extracted from. This representation is named Chem Tube. Its diameter can be adjusted to the global scale of the 3D model as all tubes entities generated with HEROS3D. To visualise the temporal evolution of the chemical concentration of the parameter of interest, the symbology colour of Chem Tube can be adapted to the chemical value for each time interval. The Chem Tubes entities for concentration of chloride in La Sagrera study site can be visualised in Fig. 6.

3.4.2 Screen Tubes

Additionally, in multi-aquifer systems, HEROS3D enables to visualise the screened interval of the well to show which aquifer has been sampled. Screen tubes are entities repre-

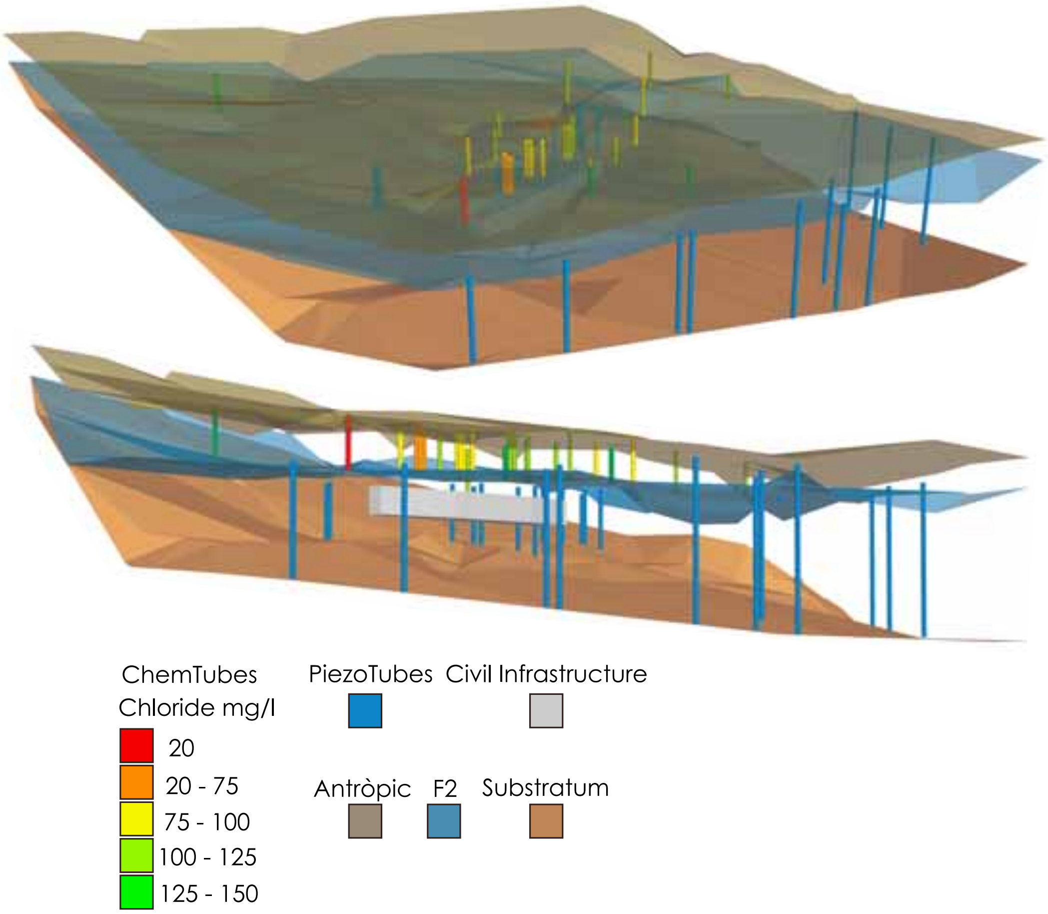

Fig. 6: Piezo and Chem Tubes of the study area. Infrastructure: 566 metres long. Vertical exaggeration factor: 15.

senting the depth and length of screens of each groundwater point.

3.5 3D geothermal data management: thermal disturbance plumes

The main methods for making use of Shallow Geothermal Energy (SGE) are the ground heat pumps systems, classified in open and closed-loop systems. Open-loop systems are pumping wells, which extract groundwater from the aquifer to make the heat exchange. After that, the groundwater, whose temperature has been altered, is reinjected into the aquifer. By contrast, closed-loop systems are vertical boreholes with a heat exchanger inside them known as Borehole Heat Exchangers (BHE). The heat is extracted or dissipated directly with the ground, without varying the hydraulic regime of the aquifer. In both cases, the exploitation of this energy resource adds a new physical impact to groundwater by altering the temperature of the underground media.

The shallow geothermal analysis in the HEROINE platform is carried out with MetroGeother tools for closed-loop systems (Alcaraz et al. 2016). This set of tools provides methodologies to facilitate the visualisation and management of the geothermal data and thermal impacts generated in the two-dimensional space. The thermal plume produced by the exploitation of SGE can be drawn with these tools in the plane X-Y. In cases where the closed-loop system crosses units with different hydraulic and thermal properties, the thermal impacts will be different for each geological or hydrogeological unit. The 3D visualisation of these thermal impacts can help to manage this resource, and distribute the thermal impact among existing exploitations and affected geological units.

A synthetic exploitation of SGE with a closed-loop system was generated. The SGE exploitation goes across the F2 unit, whose thermal impacts can be visualised in Fig. 7. This can help to optimise the depth of heat exchangers and to allocate this resource among users in an efficient manner.

4. Conclusions

HEROS3D offers a working environment for managing, querying and interpreting geological, hydrogeological, hydrogeochemical and geothermal data in a 3D GIS environment, along with additional data, such as 3D urban infra-

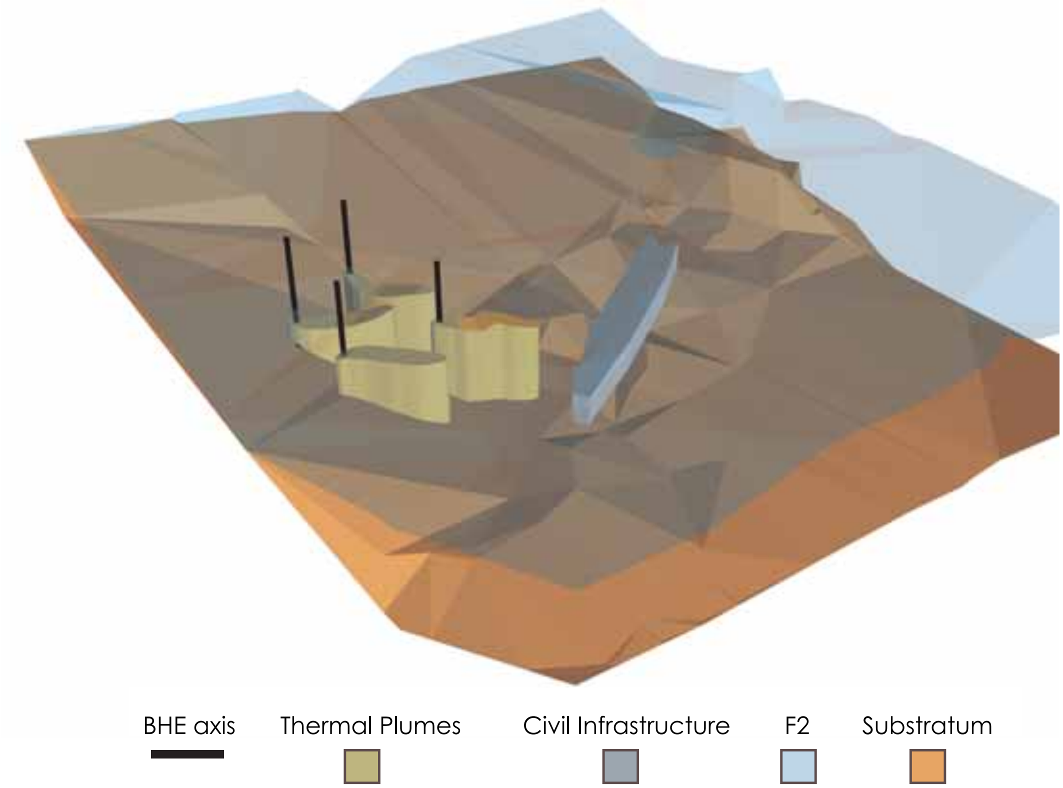

Fig. 7: Synthetic analysis of several exploitations of SGE in the study area. These thermal plumes have been calculated for a Darcy velocity of 10^{-7} m/s, a thermal conductivity of 2.6 W/K · m, a volumetric heat capacity of 3 223 000 J/K · m^3 for a heat rate of 100 W/m after a period of exploitation of 6 months. Infrastructure: 566 metres long. Vertical exaggeration factor: 15.

structures. The methodology shown here generates an initial version of the geological model. Further details must be checked and validated using both HEROS and HEROS3D in an iterative process. Complex geological geometries, such as fractures, faults or folds, cannot be managed automatically with HEROS3D, so further post-processing analysis should be required in these cases.

The geospatial database HYDOR allows us to store and manage data from hydrogeological and geological studies. Additionally, the possibility of querying and visualising all the available information in the same 3D environment gives us the possibility of integrating the geological and hydrogeological information with other relevant data (e.g. hydrogeochemical or geothermal data) and thus to obtain further information. HEROS3D is linked to the structure and format of HYDOR, so till the date, other DBMS are not supported.

Apart from the database, the presented platform offers a great variety of automatic tools developed in ArcScene (ArcGIS; ESRI) designed to exploit the stored data. Using these tools in conjunction with the rest of ArcScene capabilities increases the functionality of the software, which supports a 3D geological modelling and a subsequent comprehensive geological and hydrogeological analysis. 3D visualisation of geological interpretation can be generated automatically in different entities, such as Borehole Tubes, geological surfaces and fence diagrams. In addition, hydrogeochemical and geothermal impacts can be visualised in three-dimensional space along with the geological and hydrogeological models.

The three-dimensional visualisation of input and output data generated in each step of hydrogeological modelling supports and improves the management and understanding of available data to achieve its integration and validation during the construction of comprehensive hydrogeological models.

5. References

Alcaraz, M., García-Gil, A., Vázquez-Suñé, E. & Velasco, V. (2016): Use rights markets for shallow geothermal energy management. – Applied Energy, 172: 34–46.

Angelotti, A., Alberti, L., La Licata, I. & Antelmi, M. (2014): Energy performance and thermal impact of a borehole heat exchanger in a sandy aquifer: Influence of the groundwater velocity. – Energy Conversion and Management, 77: 700–708.

Attard, G., Winiarski, T., Rossier, Y. & Eisenlohr, L. (2015): Review: Impact of underground structures on the flow of urban groundwater. – Hydrogeology Journal, 24: 5–19.

Capozza, A., De Carli, M. & Zarrella, A. (2013): Investigations on the influence of aquifers on the ground temperature in ground-source heat pump operation. – Applied Energy, 107: 350–363.

Chesnaux, R., Lambert, M., Walter, J., Fillastre, U., Hay, M., Rouleau, A., Daigneault, R., Moisan, A. & Germaneau, D. (2011): Building a geodatabase for mapping hydrogeological features and 3D modeling of groundwater systems: application to the Saguenay–Lac-St.-Jean region, Canada. – Comput. Geosci., 37 (11): 1870–1882.

Cox, M.E., James, A., Hawke, A. & Raiber, M. (2013): Groundwater Visualisation System (GVS): a software framework for integrated display and interrogation of conceptual hydrogeological models, data and time-series animation. – J. Hydrol., 491: 56–72.

Criollo, R., Velasco, V., Vàzquez-Suñé, E., Serrano-Juan, A., Alcaraz, M. & García-Gil, A. (2016): An integrated GIS-based tool for aquifer test analysis. – Environmental Earth Sciences, 75; DOI: 10.1007/s12665-016-5292-3.

De Rienzo, F., Oreste, P. & Pelizza, S. (2008): Subsurface geological-geotechnical modelling to sustain underground civil planning. – Eng. Geol., 96 (3–4): 187–204.

Font-Capó, J., Vázquez-Suñé, E., Carrera, J., Martí, D., Carbonell, R. & Pérez-Estaun, A. (2011): Groundwater inflow prediction in urban tunneling with a tunnel boring machine (TBM). – Eng. Geol., 121: 46–54.

García-Gil, A., Vázquez-Suñe, E., Schneider, E.G., Sánchez-Navarro, J.Á. & & Mateo-Lázaro, J. (2015): Relaxation factor for geothermal use development – criteria for a more fair and sustainable geothermal use of shallow energy resources. – Geothermics, 56: 128–137.

GHS-UPC (2003): Visual Transin Code 1.1 R65. Developed in the Department of Geotechnical Engineering and Geosciences (ETCG), UPC.

Gill, B., Cherry, D., Adelana, M., Cheng, X. & Reid, M. (2011): Using three-dimensional geological mapping methods to inform sustainable groundwater development in a volcanic landscape, Victoria, Australia. – Hydrogeology Journal, 19 (7): 1349–1365.

Hähnlein, S., Bayer, P., Ferguson, G. & Blum, P. (2013): Sustainability and policy for the thermal use of shallow geothermal energy. – Energy Policy, 59: 914–925.

Howard, K.W.F. & Israfilov, R. (2002): Current problems of hydrogeology in urban areas, urban agglomerates and industrial centres, Series IV: Earth and Environmental Sciences, vol. 8: 500 p., Dordrecht (Kluwer).

INSPIRE (2011): Infrastructure for spatial information in Europe. D2.9_V1.0. Guidelines for the use of observations & measurements and sensor web enablement-related standards in INSPIRE. Annex II and III data specification development.

INSPIRE (2013): Infrastructure for spatial information in Europe. D.2.8.11.4. Data specification on geology – draft technical guidelines.

Jurado, A., Vàzquez-Suñé, E., Carrera, J., López de Alda, M., Pujades, E. & Barceló, D. (2012): Emerging organic contaminants in groundwater in Spain: a review of sources, recent occurrence and fate in a European context. – Sci. Total Environ., 440: 82–94.

Koller, D., Lindstrom, P., Ribarsky, W., Hodges, L.F., Faust, N. & Turner, G. (1995): Virtual GIS: a real-time 3D geographic information system. – In: Proceedings IEEE Conference on Visualization, 1995: 94–100, 443.

Lerner, D.N. (1996): Guest editor's preface: theme issue on urban groundwater. – Hydrogeology Journal, 4: 4–5.

Lo Russo, S. & Civita, M.V. (2009): Hydrogeological and thermal characterization of shallow aquifers in the plain sector of Piemonte region (NW Italy): implications for groundwater heat pumps diffusion. – Environmental Earth Sciences, 60 (4): 703–713.

McDonald, M. & Harbaugh, A. (2003): The history of MODFLOW. – Ground Water, 41 (2): 280–283.

ONEGeology (2013): ONEGeology project. Available at: www.onegeology.org. Accessed 13/10/2015.

OGC (2012): OGC WaterML 2.0: Part 1 – Timeseries, 10-126r3.

Pujades, E., López, A., Carrera, J., Vázquez-Suñé, E. & Jurado, A. (2012): Barrier effect of underground structures on aquifers. – Eng. Geol., 145–146: 41–49.

Ross, M., Parent, M. & Lefebvre, R. (2005): 3D geologic framework models for regional hydrogeology and land-use management: a case study from a Quaternary basin of southwestern Quebec, Canada. – Hydrogeology Journal, 13: 690–707.

Schirmer, M., Leschik, S. & Musolff, A. (2013): Current research in urban hydrogeology – a review. – Adv. Water Resour., 51: 280–291.

Strassberg, G., Jones, N.L. & Lemon, A. (2010): Arc hydro groundwater data model and tools: overview and use cases. – AQUA Mundi (2010) – Am02014: 101–114.

Tait, N.G., Davison, R.M., Whittaker, J.J., Leharne, S.A. & Lerner, D.N. (2004): Borehole Optimisation System (BOS) – a GIS based risk analysis tool for optimising the use of urban groundwater. – Environmental Modelling & Software, 19 (12): 1111–1124.

Tame, C., Cundy, A.B., Royse, K.R., Smith, M. & Moles, N.R. (2013): Three-dimensional geological modelling of anthropogenic deposits at small urban sites: a case study from Sheepcote Valley, Brighton, UK. – Journal of Environmental Management, 129: 628–634.

Thierry, P., Prunier-Leparmentier, A.M., Lembezat, C., Vanoudheusden, E. & Vernoux, J.F. (2009): 3D geological modelling at urban scale and mapping of ground movement susceptibility from gypsum dissolution: the Paris example (France). – Eng. Geology, 105 (1–2): 51–64.

Trefry, M.G. & Muffels, C. (2007): FEFLOW: A finite-element ground water flow and transport modeling tool. – Ground Water, 45 (5): 525–528.

Tropp, O., Tal, A. & Shimshoni, I. (2006): A fast triangle to triangle intersection test for collision detection. – Computer Animation and Virtual Worlds, 17 (5): 527–535.

Turner, A.K. (2006): Challenges and trends for geological modelling and visualisation. – Bull. Eng. Geol. Env., 65 (2): 109–127.

Turner, R.J., Mansour, M.M., Dearden, R., Ó Dochartaigh, B.É. & Hughes, A.G. (2014): Improved understanding of groundwater flow in complex superficial deposits using three-dimensional geological-framework and groundwater models: an example from Glasgow, Scotland (UK). – Hydrogeology Journal, 23: 493–506.

Vázquez-Suñé, E., Sánchez-Vila, X. & Carrera, J. (2005): Introductory review of specific factors influencing urban groundwater, an emerging branch of hydrogeology, with reference to Barcelona, Spain. – Hydrogeology Journal, 13 (3): 522–533.

Vázquez-Suñé, E., Marazuela, M.A., Velasco, V., Diviu, M., Pérez-Estaún, A. & Álvarez-Marrón, J. (2016): A geological model for the management of subsurface data in the urban environment of Barcelona and surrounding area. – Solid Earth, 7: 1317–1329.

Velasco, V., Cabello, P., Vázquez-Suñé, E., López-Blanco, M., Ramos, E. & Tubau, I. (2012a): A sequence stratigraphic based geological model for constraining hydrogeological modeling in the urbanized area of the Quaternary Besòs delta (NW Mediterranean coast, Spain). – Geologica Acta, 10: 373–393.

Velasco, V., Gogu, R., Vázquez-Suñè, E., Garriga, A., Ramos, E., Riera, J. & Alcaraz, M. (2012b): The use of GIS-based 3D geological tools to improve hydrogeological models of sedimentary media in an urban environment. – Environmental Earth Sciences, 68 (8): 2145–2162.

Velasco, V., Tubau, I., Vázquez-Suñè, E., Gogu, R., Gaitanaru, D., Alcaraz, M., Serrano-Juan, A., Fernández-García, D., Garrido, T., Fraile, J. & Sanchez-Vila, X. (2014): GIS-based hydrogeochemical analysis tools (QUIMET). – Comput. Geosci., 70: 164–180.

Wagner, V., Blum, P., Kübert, M. & Bayer, P. (2013): Analytical approach to groundwater-influenced thermal response tests of grouted borehole heat exchangers. – Geothermics, 46: 22–31.

Wycisk, P., Hubert, T., Gossel, W. & Neumann, C. (2009): High-resolution 3D spatial modelling of complex geological structures for an environmental risk assessment of abundant mining and industrial megasites. – Comput. Geosci., 35 (1): 165–182.

Manuscript received: 30.10.2015
Accepted for publication: 13.05.2016