Developing tools for a better incorporation of geoscientific knowledge in policy making for a densely populated region

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The need for a more efficient use of the subsurface in tackling a variety of issues is becoming more apparent, certainly in densely populated regions. For a better incorporation of geological knowledge into policy making, e.g., related to underground space use, raw materials management and (deep) subsurface planning for technologies such as geothermal energy, it is essential to develop user-friendly tools. These can translate geological information to field applications, which can be understood by policy officers, engineers, architects, etc. In Flanders (Belgium), such tools are developed and published on an open platform. Even though many tools are already available based on extensive 3D geological models, advances can still be made towards voxel models and 2D maps combining information for specific purposes.

La nécessité d'une utilisation plus efficace du sous-sol pour résoudre divers problèmes devient de plus en plus évidente, notamment dans les régions densément peuplées. Pour une meilleure intégration des connaissances géologiques dans l'élaboration des politiques, par exemple en ce qui concerne l'utilisation de l'espace souterrain, la gestion des matières premières et la planification du sous-sol (profond) pour des technologies telles que l'énergie géothermique, il est essentiel de développer des outils conviviaux. Ceux-ci peuvent traduire les informations géologiques en applications sur le terrain, qui peuvent être comprises par les responsables politiques, les ingénieurs, les architectes, etc. En Flandre (Belgique), de tels outils sont développés et publiés sur une plateforme ouverte. Même si de nombreux outils basés sur des modèles géologiques 3D étendus sont déjà disponibles, des progrès peuvent encore être réalisés vers des modèles voxels et des cartes 2D combinant des informations à des fins spécifiques.

La necesidad de un uso más eficiente de la subsuperficie para abordar una variedad de temas está siendo más aparente, especialmente en zonas densamente pobladas. Para una mejor incorporación del conocimiento geológico en el desarrollo de políticas, e.g., relacionadas con el uso del espacio subterráneo, manejo de materia prima y planificación de subsuperficie (profunda), para tecnologías tales como energía geotermal, es esencial el desarrollo de herramientas fáciles de usar. Estas pueden traducir la información geológica a campos de aplicación que puedan ser comprendidos por los encargados de gestionar las políticas de desarrollo, ingenieros, arquitectos, etc. En Flandes (Bélgica), esas herramientas son desarrolladas y publicadas en una plataforma abierta. Aunque ya existen muchas herramientas disponibles basadas en modelos geológicos 3D, se pueden crear nuevos desarrollos con modelamiento Voxel y mapas 2D, combinando información para propósitos específicos.

1. Introduction

The region of Flanders is one of the most densely populated regions of Europe, with a population density of 492 inhabitants/km^2 [1], compared to the European Union average of 109 inhabitants/km^2 [2]. The settlement area [3] in Flanders is 33 % of the total surface area [4]. In such a dense region there is significant stress on the available land surface area. Due to soil sealing by roads, housing, infrastructure, etc. the soil and the subsurface can no longer optimally carry out their natural geosystem services. This leads to a loss of biodiversity, reduced ground water recharge, the urban heat island effect, and more [5-8].

A shift towards a 3D perspective of our available space, thus incorporating the subsurface dimension, must be part of the solution, as density of functions can be increased in certain areas, while freeing land surface in others. The urban subsurface is considered a valuable, multifunctional natural resource that provides different (geosystem) services, such as groundwater, energy potential, geomaterials, carbon sequestration, heritage and underground infrastructures [5, 9, 10]. The use of the shallow subsurface for infrastructure purposes remains predominantly characterised by an ad-hoc, first-come, first-served, or last-resort approach [11-13]. This leads to scattered development of solitary projects, conflicts, competition, and unintentional consequences arising from unforeseen interactions with other underground services. Such practices are detrimental to the sustainable development of the urban environment and are likely caused by a lack of knowledge, foresight and planning [14-17].

A high population density requires a significant number of natural resources, leading to further depletion of groundwater levels and possible exhaustion of minerals and industrial materials. Ways to meet the demand include import, recycling, technological innovations and behavioural change [18, 19], yet domestic extraction of primary materials remains part of the equation [20]. Additionally, energy demand is high while available surface area for renewable sources such as wind and solar is limited. Geothermal

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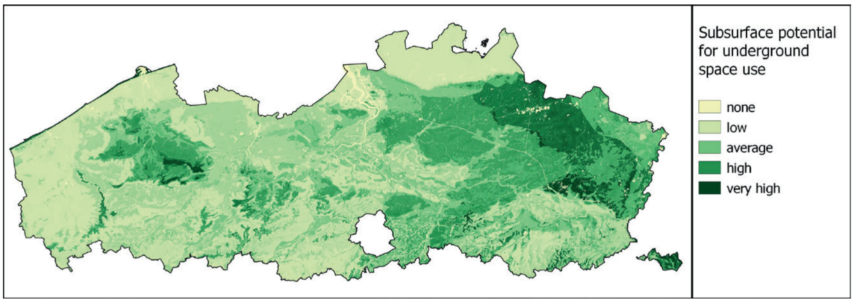
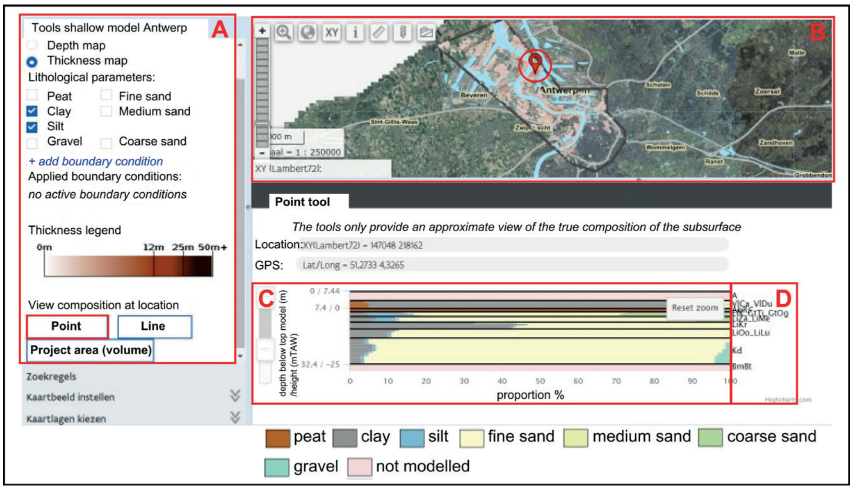


Figure 1: Map illustrating the subsurface's suitability for underground construction at depths ranging from 0 to 9 m below the surface. Suitability was calculated by incorporating information on settlement sensitivity of the (sub)soil, raw material potential, water saturation and pollution.


Tools shallow model Antwerp

○ Depth map
● Thickness map

Lithological parameters:

☐ Peat ☐ Fine sand
☑ Clay ☐ Medium sand
☑ Silt
☐ Gravel ☐ Coarse sand

+ add boundary condition

Applied boundary conditions:

no active boundary conditions

Point tool

The tools only provide an approximate view of the true composition of the subsurface

Location: XY(Lambert72) = 147048 218162

GPS: Lat/Long = 51,2733 4,3265

Figure 2: Image from the online viewer of the shallow subsurface voxel model of the Antwerp urban area, available on DOV [29]. (A) In the interface the user can choose to visualise a depth or thickness map and can choose which lithologies to visualise, together with secondary conditions such as minimal thickness of selected lithologies. Also, the point, line and volume calculation features are available. (B) The map shows the outline of the modelled area, in this example with a thickness map for the selected parameters clay and silt. (C) A 'virtual core' of the model is shown, at the location indicated on the map, in which the lithological composition for each voxel can be viewed, alongside the division into geological units (D). The key text was translated to English for the purpose of this figure, however the language of the online tool is Dutch.

energy provides a potential solution, however even the subsurface has its spatial limitations and planning of the (deep) subsurface is necessary to ensure an efficient exploitation of the available potential [21].

In this paper, multiple tools developed by the Department of Environment and Spatial Development of the Flemish Government and their relation to policy are presented. These tools are developed to unlock the subsurface potential for challenges related to underground space use, raw materials, and planning of the (deep) subsurface for emerging technologies such as geothermal energy.

2. Underground space use

As a result of the region's significant settlement area, Flanders has a high degree of man-made soil sealing [22] surfaces (15 % compared to an EU average of 2.3 % in 2006) [3, 23]. The high degree of soil sealing places a substantial strain on the environment, as soils are destroyed, and water can no longer infiltrate to replenish ground water levels [24].

To counteract these trends a shift in planning policy was instigated [25], which focuses on preserving open spaces and aims to halt urban sprawl by reducing the daily land consumption from six hectares in 2016 to zero hectares by 2040. Although the strategic vision briefly acknowledges the potential use of the subsurface to increase density, it lacks elaboration. In recent years an increasing number of municipalities and regions in Europe are becoming aware of the benefits of urban underground space (UUS) use [26], including the Flemish Government. Parallel to the development of the *Spatial Policy Plan Flanders* (2018), a policy exploration was launched to examine whether efficient use of UUS could be an additional solution for lowering the daily land consumption [27]. Cooperation between geo-scientists and urban planners is of utmost importance when developing subsurface policy. Ideally policy on subsurface infrastructures should be integrated in an overall vision/strategy of land use and urban planning, above and below the subsurface. In 2021 the Flemish Government launched the *fourth Flemish Strategy on Sustainable Development* [28], which includes an initiative aimed at sustainable UUS use. To aid the local and regional development of subsurface policy several tools/instruments are being launched such as a planning framework based on geosystemic considerations and an online policy guide for UUS planning.

In order to identify areas where underground space can be optimally developed, opportunity maps for underground space use are useful tools. Within Flanders, geologists, geographers, and policy makers are working together to develop a framework on the different surface and subsurface parameters to consider when promoting UUS. These parameters include the spatial context, settlement risk, raw material potential and geotechnical potential and associated risks [27]. These dimensions are combined and converted to simple maps, providing clear information about the potential of UUS in different areas of Flanders (Figure 1).

The open publication of subsurface 3D models, in combination with tailor-made and easy to use functionalities, raises subsurface awareness and enhances the understanding of policy makers, industry and citizens. This approach enables the exploration of the varied composition of the subsurface, thereby facilitating a more sustainable and effective management of the urban subsurface. Standard geological 3D models are layer-cake representations, dividing the subsurface into geological units. Nevertheless, it is crucial to note that, geological units are often not homogenous. To account for heterogeneity and to get a more detailed picture of the composition of the subsurface voxel models can be created. In these models, each voxel, or 3D pixel, has a value for certain parameters such as lithological composition. The Antwerp urban area and its port was chosen as the first test area to develop a shallow urban voxel model in Flanders [30]. The major infrastructure works in that area offered new field data and

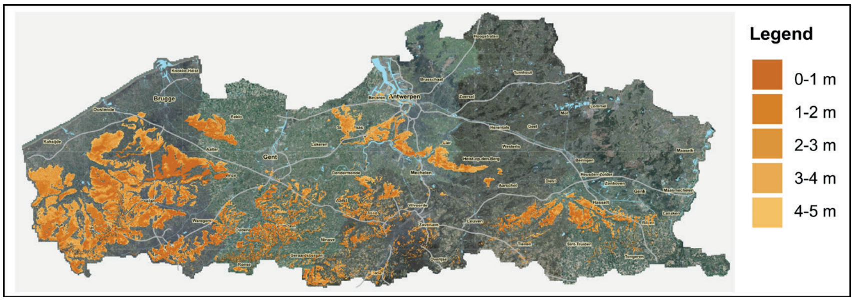


Figure 3: Map from the specialised DOV viewer [29] for the possible occurrence of swelling clays, showing the depth of the top of clayey Neogene or Paleogene units within the top 5 m below the surface.

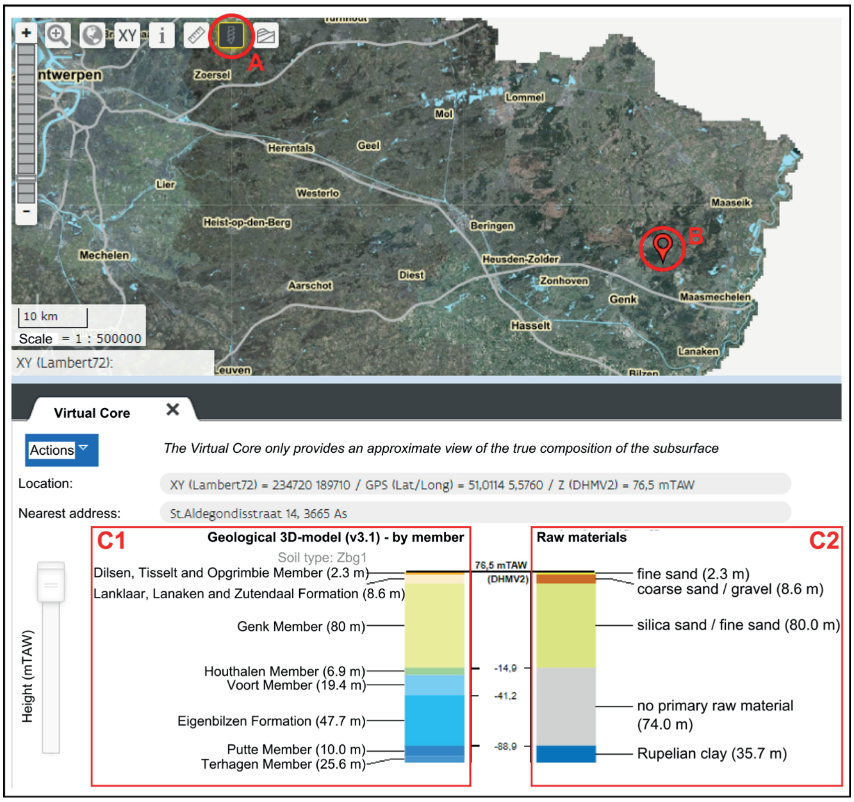
the opportunity to refine the geological interpretations. In addition, these infrastructure works challenge environmental policy officers and project developers to increase their understanding of the composition and potential applications of the subsoil. The voxel model includes new data and geological insights, facilitating further knowledge building of Antwerp's subsurface. The dedicated online viewer enables geological, hydrogeological and geotechnical prospection and promotes the inclusion of subsurface data in geothermal projects, temporary dewatering, re-use of excavated soil, stability studies, infiltration projects etc. The variation in the lithological composition can be consulted at a point location or along a vertical profile (Figure 2). In addition, it is possible to calculate the volumes of the lithologies for various areas and depth ranges. Compositional information is given when querying the voxel model results.

Geological maps and models are also an important asset for regional risk mapping and management. The standardised data management of the composing elements in DOV (database of the subsurface of Flanders) [31] allows to derive hazard maps for different purposes at different scales, making them accessible to non-professional geologists. For example, certain geological layers consist, at least partly, of swelling and shrinking clays. On DOV, a map view for potentially swelling (sub)soils in Flanders is available (Figure 3) based on the geological 3D model [32] and the Digital Soil Map [33]. These clays can potentially cause damage to buildings due to fluctuations in water content, particularly of swelling clays such as smectite, found underneath foundations [34]. Further ongoing research should provide a preliminary risk map on swelling clays in the Flemish subsurface. The 3D distribution of these smectite-rich units, laboratory analyses of borehole samples, damage inventory, site investigations and geological expertise, enable a hazard assessment of the anticipated geological composition at a specific site. The results of this research should support the development of a more climate-resilient housing policy.

3. Raw Materials

In densely populated regions, such as Flanders, the demand on mineral resources is high, yet both the space and the public acceptance for new or existing quarries is very limited [35]. Raw materials extracted in Flanders are clay, loam, sand and gravel for the construction industry and white silica sand for glass and high-tech applications. The extraction is mainly regulated through the *Flemish Parliament Act on Surface Mineral Resources* (2003). This policy's basic objective is to have a sustainable supply of the necessary mineral resources to meet the current and future demand of society. In the periodically reviewed *General Surface Mineral Resources Plan (AOD)* [36], the reserves in the areas designated for mineral extraction are assessed in comparison to the demand for the raw materials, and proposals made for future actions are formulated. Required knowledge for the monitoring of mineral resources, in addition to the reserves, includes data on alternatives for the primary raw materials, production and use of all relevant materials and import and export flows. This information is periodically collected by the *Monitoring system for a Sustainable Surface mineral resources Policy (MDO)* [37]. For possible future scenario's, a stock-flow model is available.

Excavated geological layers, such as infrastructure projects are also potential resources. Developers are obliged to assess whether any economically valuable layers may be excavated during a project in advance, as these are an important alternative for primary sources from quarries.

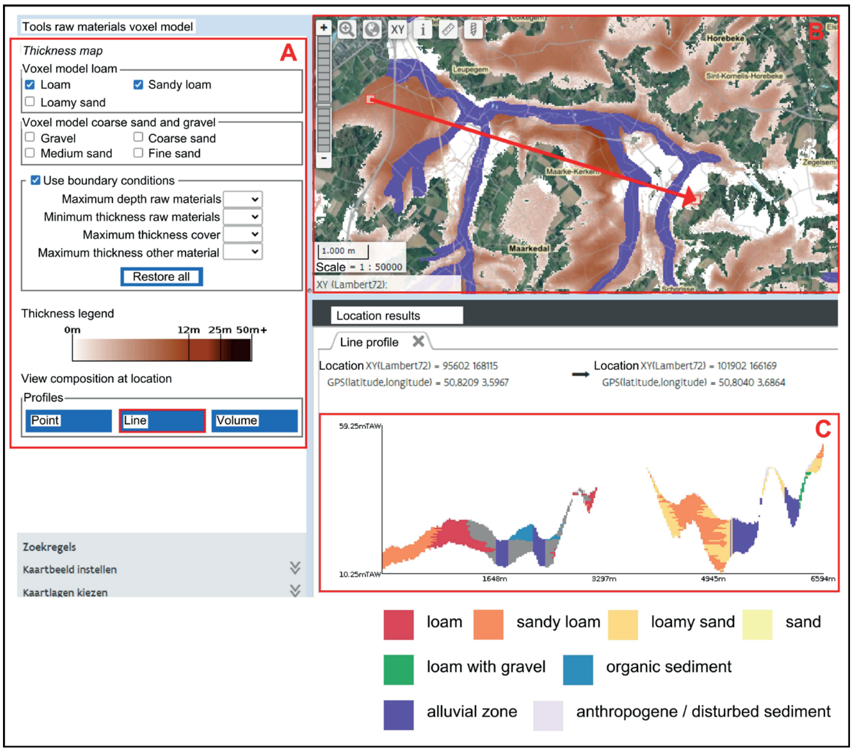


The Virtual Core only provides an approximate view of the true composition of the subsurface

Location: XY (Lambert72) = 234720 189710 / GPS (Lat/Long) = 51,0114 5,5760 / Z (DHMV2) = 76,5 mTAW

Nearest address: St.Aldegondisstraat 14, 3665 As

Figure 4: Visualisation of the raw materials model in the 'Virtual Core' of DOV [29]. The virtual core tool (A) can be selected at the top of the map viewer. With the tool an activated location on the map (B) can be selected. The result is shown below. In this example, the raw material model (C2) is compared to the geological members of the geological 3D model (G3Dv3.1) (C1). The key text was translated to English for the purpose of this figure, however the language of the online tool is Dutch.



Thickness map

Voxel model loam
☑ Loam ☑ Sandy loam
☐ Loamy sand

Voxel model coarse sand and gravel
☐ Gravel ☐ Coarse sand
☐ Medium sand ☐ Fine sand

☑ Use boundary conditions
Maximum depth raw materials
Minimum thickness raw materials
Maximum thickness cover
Maximum thickness other material

Thickness legend
0m 12m 25m 50m+

View composition at location

Profiles

Location XY(Lambert72) = 95602 168115
GPS(latitude,longitude) = 50,8209 3,5967
→ Location XY(Lambert72) = 101902 166169
GPS(latitude,longitude) = 50,8040 3,6864

🟥 loam 🟧 sandy loam 🟨 loamy sand 🟨 sand
🟩 loam with gravel 🟦 organic sediment
🟪 alluvial zone ⬜ anthropogene / disturbed sediment

Figure 5: The specialised map viewer of the raw materials voxel models in DOV [29], with (A) the interface where lithologies of interest can be selected, as well as secondary conditions such as thickness of overburden, and the tools for point and line sections and volume calculations, (B) the map view with a thickness map of the selected lithologies – loam and sandy loam in this example – and a profile line added in this example with the result below, (C) where the vertical profile through the voxel model is shown, in which the Quaternary is divided into different lithologies. The key text was translated to English for the purpose of this figure, however the language of the online tool is Dutch.

Thanks to a detailed geological 3D model [32], which divides the subsurface into formally defined geological formations and members it is possible to make an educated estimate about the geological units present at any location in Flanders. In DOV tools like the 'Virtual Core' and 'Virtual Profile' are available which allow any user to visualise the geological composition of the subsurface, based on the available models, at any point or in a 2D transect along any line. Regarding existing and former quarries, there is also information available about which materials are being excavated and to which geological units these belong. Based on this information, a translation was made from the geological model to a raw materials model. The incorporation of this model into the 'Virtual Core' and 'Virtual Profile' tools, as well as presenting it as separate map layers for the shallow occurrence of each raw material unit, enables the possibility for quick assessment of the potential of valuable raw materials at any excavation site (Figure 4), which may then be selectively excavated and valorised.

For a more detailed and accurate representation of the subsurface from a raw materials perspective, two voxel models were created for materials with a shallow and geographically confined occurrence. One in the southern part of the region, where loamy aeolian deposits occur close to the surface [38] and another in the east of Flanders, where coarse sand and gravel units related to the Rhine and Meuse rivers occur at shallow depth [39]. A specialised map viewer was developed in DOV for these models, along with tools, such as virtual core, profile and volume calculations (Figure 5). These models enable companies already active in quarrying materials to locate the best deposits. They also allow infrastructure companies to assess whether any valuable materials may be excavated during a certain upcoming project, although confirmation through field research remains necessary.

4. Planning of the deep subsurface

The subsurface can play a key role in the energy and climate transition by adding geothermal energy, hydrocarbon storage and heat storage to the energy mix. Not only does the subsurface contain energy sources in itself, but it also offers large reservoir spaces where energy deficits or overproduction from (renewable) sources at the surface can be buffered on seasonal scale [40]. Geological layers with suitable characteristics and conditions for these applications, mainly the lower Carboniferous limestone, are not equally distributed in Flanders, leading to pressure on the available space and competition at depth. A thoughtful vision for subsurface allocation is essential for an optimal deployment of subsurface applications and to preserve its potential for future generations. The *Flemish Decree on the deep subsurface* (2009) contains rules for efficient planning. Exploration and exploitation volumes need to be strictly delimited in three dimensions based on an acceptable subsurface impact radius, so to avoid negative impacts on neighbouring activities while being as efficient as possible. Stacking of volumes and combining activities is allowed under certain conditions (Figure 6). Nearby projects need to tune their operational works. If required, the Flemish Government can intervene in the collaboration to ensure efficient use of the subsurface. The decree also stipulates that a structural vision for the deep subsurface needs to be developed. This instrument is in development and will foresee a complete overview of the legal aspects, Flanders' geology, an inventory of potential applications with their boundary conditions, active permits, time and space relationships of all potential activities and an assessment framework. The latter aims at providing insights into the opportunities and challenges of the deep subsurface and into the impacts of certain policy choices. Policy makers will be able to use this assessment framework as base for their policies. This structural vision is not legally binding, nor is it a subsurface register which stipulates what should be done at each location. However, it is a strategic ex ante instrument which can help in concrete permit decisions to avoid ill-considered ad hoc destination which could jeopardise the needs of current and future generations.

Being efficient in a densely occupied subsurface requires detailed geological knowledge. In addition to the implementation of the Flemish Decree on the deep subsurface, a three dimensional layer and fault model is being developed for the deep subsurface [32, 41] and targeted research assignments are commissioned regularly to increase knowledge and insights on the geology, the valorisation potential

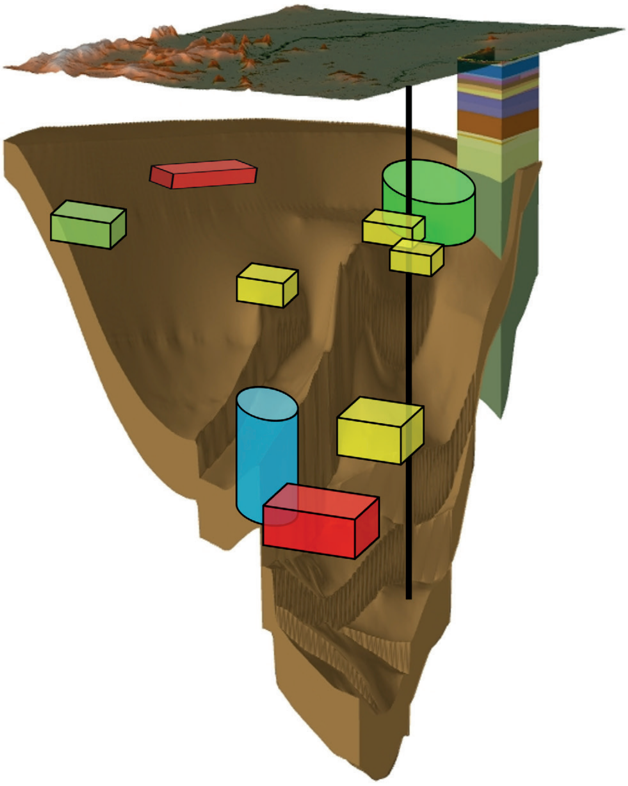
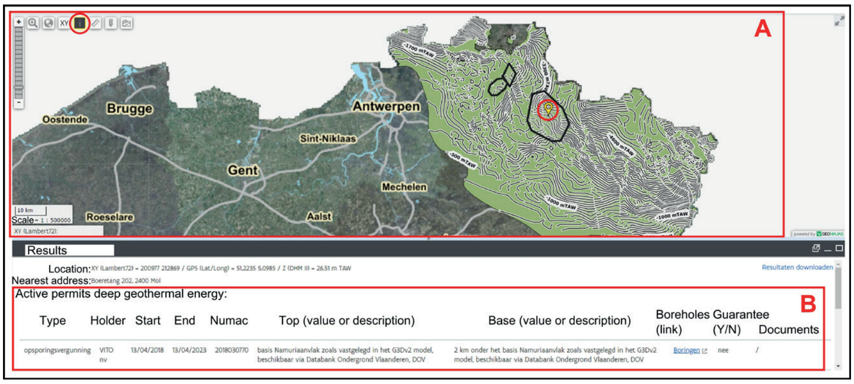


Figure 6: Schematic illustration of the principle of 3D permits whereby different applications may occur next to or above each other. Geological visualisation of the Campine Basin, with the Devonian layer at the base (brown) on top of the London-Brabant Massif, in which the deepest subsurface applications in Flanders are possible. The model column shows a cross-section through the 3D geological model from base to top.



Location: XY (Lambert72) = 200977 212869 / GPS (Lat/Long) = 51,2235 5,0985 / Z (DHM II) = 26,51 m TAW
Nearest address: Boeretang 202, 2400 Mol

Active permits deep geothermal energy:

Type	Holder	Start	End	Numac	Top (value or description)	Base (value or description)	Boreholes (link)	Guarantee (Y/N)	Documents
opsporingsvergunning	VITO nv	13/04/2018	13/04/2023	2018030770	basis Namuriaanvlak zoals vastgelegd in het G3Dv2 model, beschikbaar via Databank Ondergrond Vlaanderen, DOV	2 km onder het basis Namuriaanvlak zoals vastgelegd in het G3Dv2 model, beschikbaar via Databank Ondergrond Vlaanderen, DOV	Boringen	nee	/

Figure 7: Map view in the DOV viewer [29], illustrating (A) the occurrence of the Dinantian limestones (in green), in which multiple applications such as geothermal energy, gas storage and carbon storage are possible, overlain with the isohypses of the top of the Dinantian, both based on the G3Dv3.1 geological 3D model. The active permits for deep geothermal energy are also shown on top. By clicking on these layers more information can be gathered, such as shown below (B) for the active permits, e.g. type of permit, start date, end date, top, base, related cores and coupled documents. The key text was translated to English for the purpose of this figure, however the language of the online tool is Dutch.

of the subsurface, geohazards associated with subsurface development and other aspects for an efficient and responsible management of the subsurface [42]. Both geological information as well as administrative information on existing permits is made publicly available through DOV (Figure 7), where governments and private companies can gather information for the exploration of possible future opportunities.

5. Future perspectives

As one of Europe's most densely populated regions, Flanders will continue its current trajectory towards better surface and subsurface planning and a more optimal management of its resources. As demonstrated in this article, geological knowledge is becoming increasingly important for the realisation and implementation of policies related to multiple domains, such as resources, energy, spatial planning, and climate. Even though an interesting set of tools has already been developed, there is still room for improvement. In the future more focus must be on a better translation of geological knowledge towards field applications, which can be readily understood by non-geoscientists such as policy officers, engineers, architects, etc. In order to achieve this, the current well-developed regional 3D layer model of the subsurface should be converted into a voxel model, which can be filled in with multiple parameters, e.g. related to geotechnical, geothermal or hydrological properties. Easy to interpret 2D maps combining multiple types of geological and other data to show applied information for specific use are perhaps the best tools for communication with non-experts. Of course, continued investment in new data and geological knowledge remains key for the creation of better maps and models. Lastly, a better integration must be realised between surface and (deep) subsurface information to incorporate the subsurface dimension into planning processes and to gain more insight into both the opportunities and risks related to the subsurface, which can be used in an earlier phase of planning processes thanks to accessible geological tools.

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