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Subsurface planning: Towards a common understanding of the subsurface as a multifunctional resource

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ABSTRACT

In response to powerful trends in technology, resource and land supply and demand, socioeconomics and geopolitics, cities are likely to increase use of the subsurface in the near future. Indeed, the subsurface and its appropriate use have been put forward as being of crucial importance if we are to achieve resilient and sustainable cities. In recent years, quite apart from being seen primarily as a construction basis to provide physical space for infrastructure and to create a better surface living environment, the subsurface has been recognised as a multifunctional natural resource, one which provides physical space, water, energy, materials, habitats for ecosystems, support for surface life, and a repository for cultural heritage and geological archives. Currently, the subsurface is often utilised according to the "first-come-first-served" principle, which hinders possibilities to take strategic decisions on prioritisation and optimisation of competing subsurface uses, as well as fair inter- and intragenerational distribution of limited natural resources. Taking a broad international perspective, this paper investigates the subsurface as a multifunctional resource from five focal points: (1) what professionals with different backgrounds mean when using different terms related to the subsurface; (2) how professionals describe the subsurface and its multiple resources, functions and services; (3) how planning of subsurface use is supported in policy and regulations; (4) how the subsurface is included in the planning process; and (5) frameworks that can support decision-making on responsible use of the subsurface. The study reveals that the subsurface must be recognised (not only by scientists but also by decision- and policy-makers and other stakeholders) as a precious and multifunctional resource requiring careful planning and sensitive management in accordance with its potential and its value to society. Utilisation of the different subsurface functions to yield services requires careful planning and a framework to support decision-makers in achieving a balance between utilisation and preservation, and between the subsurface functions themselves in the case of outright utilisation. Further, to facilitate the necessary change towards transdisciplinary work settings in the planning process and form a platform for knowledge exchange and capacity building, there is an urgent need for a common language, i.e. mutually understandable terminology, and a common understanding, i.e. an all-inclusive view on the subsurface as a complex multifunctional resource.

1. Introduction

1.1. Background

The phenomenal growth of the world's population coupled with rapid urbanisation and the associated demands on infrastructure and densification of the built environment impose intense pressures on land resources and on the environment in the expanding urban areas (Sterling et al., 2012; Zargarian et al., 2013; Price et al., 2016; Broere, 2016). Lack of surface space and a struggle for better living environments have been the main driving factors for an increased use of the subsurface in the world's largest and most wealthy cities (Bobylev,

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2016a,b). Along with a shortage of urban land for development, the increased interest in and use of the subsurface worldwide can be explained by the strategic objectives of the community and government to improve the environmental quality of cities, to increase their functional diversity, to enhance safety in urban communities and to preserve the urban landscape and cultural heritage (Clarke, 2000). It is expected that in the coming years more cities will require extensive use of the subsurface in response to trends in technology, resource supply and demand, socioeconomics and geopolitics (e.g. Evans et al., 2009; NRC, 2013).

The increasing use of urban underground space (UUS) is expected to contribute to achieving six out of 17 UN sustainable development goals (SDGs), namely to: ensure availability and sustainable management of water and sanitation for all (SDG6); ensure access to affordable, reliable, sustainable and modern energy for all (SDG7); promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all (SDG8); build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation (SDG9); make cities and human settlements inclusive, safe, resilient and sustainable (SDG11); and to take urgent action to combat climate change and its impacts (SDG13) (Admiraal and Cornaro, 2016a). However, development of the underground, which until rather recently has been seen as a sustainable action in itself, may not be associated with sustainable development if the broader effects on the subsurface as a multifunctional resource are not taken into consideration (Admiraal, 2006).

The traditions of humans using subsurface caves for protection and also mining date back to prehistoric times. For details on evolution of underground space uses and needs from pre-historic times until today, the reader is referred to the study by von der Tann et al. (2019). Utilisation of the subsurface in urban areas to provide physical space has been gradually increased over times. However, only in more recent years, apart from being seen primarily as a construction basis to provide physical space for infrastructure and to create a better surface living environment, the subsurface has been recognised as a multifunctional natural resource, which provides physical space, water, energy, materials, habitats for ecosystems and support for surface life, while also acting as a repository for cultural heritage and geological archives (e.g. Parriaux et al., 2004, 2007; Admiraal, 2006; Bobylev, 2009; Hooimeijer and Maring, 2013, 2018; Griffioen et al., 2014; Hallbeck and Pedersen, 2014; Thulin et al., 2014; Tummers & Hooimeijer, 2016; van Ree et al., 2017; Drake et al., 2017). Consequently, the subsurface forms manmade and natural assets, i.e. it creates a potential or actual value to society by providing services (see e.g. de Mulder and Pereira, 2009; Price et al., 2016; Bobylev, 2016a,b; van Ree and van Beukering, 2016; Maring and Blauw, 2018; Lindblom et al., 2018).

It was stressed by Webster some 100 years ago (Webster, 1914), and the point has been echoed by a great many scholars in the past 40 years (e.g. Jansson, 1976; Winqvist, 1981; Wood and Jansson, 1983; Barker, 1991; Clarke, 2000; Parriaux et al., 2004, 2007; Kaliampakos and Benardos, 2008; Admiraal, 2009; Bobylev, 2009; Evans et al., 2009; Sterling et al., 2012; Admiraal and Cornaro, 2016a; 2018; Makana et al., 2016; Hooimeijer and Maring, 2013, 2018), that use of the subsurface requires careful planning, where the subsurface with all of its embedded systems is treated as an integrated entity (von der Tann et al., 2019). This type of planning is, however, associated with several serious challenges. One main issue is to make the subsurface visible and acknowledged in spatial planning processes, because the subsurface is often "out-of-sight-out-of-mind" for decision-makers (e.g. Sterling, 1996; van der Meulen et al., 2016b; Mielby et al., 2017a; Campbell et al., 2017). A large body of studies consequently aims to address the challenge of the invisibility of the subsurface (e.g. Parriaux et al., 2004, 2007; de Mulder and Pereira, 2009; de Mulder et al., 2012; Bobylev, 2009; Hooimeijer and Maring, 2013, 2018; Griffioen et al., 2014; Makana et al., 2016; Norrman et al., 2016; van Ree et al., 2017; Maring and Blauw, 2018; Vähäaho, 2018; Lindblom et al., 2018; Mossmark et al., 2018).

Another challenge is to achieve a synergy between surface and subsurface planning (e.g. Jansson, 1976, 1978; Winqvist, 1981; Wood and Jansson, 1983; Barker, 1991; Stones and Heng, 2016), which is a vital prerequisite of the sustainable development of cities (Admiraal and Cornaro, 2016a; Besner, 2016; Norrman et al., 2016; Hooimeijer and Maring, 2018; Dick et al., 2019). Such synergies can only be achieved through: (i) deliberate knowledge exchange between professionals representing the surface and the subsurface sectors (de Mulder and Pereira, 2009; Admiraal and Cornaro, 2016b; Norrman et al., 2016; Campbell et al., 2017; Hooimeijer and Maring, 2018: Dick et al., 2019), and (ii) a cultural shift towards recognising strong interconnections between these two sectors in spatial planning processes (Hooimeijer and Maring, 2018). The quality of future developments strongly depends on such partnerships, and even though the change towards interdisciplinary working has started, the move from working in silos towards knowledge exchange between professions does not happen overnight (Besner, 2016).

The cross-cutting challenge in subsurface planning is to achieve a balance between utilisation and preservation of multiple underground resources and among the resources themselves in the case of straightforward utilisation (Admiraal, 2009; Admiraal and Cornaro, 2016a). In other words, the multifunctionality of the subsurface does create opportunities but it also creates conflicts between competing uses, e.g. geothermal installations and underground space for construction (Parriaux et al., 2004; Admiraal, 2006; Bartel and Janssen, 2016; Li et al., 2016b). Von der Tann stresses that conflicts stem from the incompatible perspectives of different stakeholder groups on the subsurface and its functions. At the same time, a common issue of growing concern around the globe is that the subsurface is usually utilised according to the "first-come-first-served" principle (e.g. Bobylev, 2009; Admiraal and Cornaro, 2016a; Bartel and Janssen, 2016; Stones and Heng, 2016; Tengborg and Sturk, 2016; Pfleiderer et al., 2016; Dick et al., 2019), which hinders: (i) structured prioritisation and optimisation of competing subsurface uses, (ii) fair inter- and intragenerational distribution of limited natural resources, and thus (iii) sustainable development of cities.

What are the bottlenecks in planning more responsible subsurface use? Insufficient support in policy and regulations? Insufficient decision support? Insufficient awareness of decision- and policy-makers? Insufficient communication between different professions? These different jigsaw puzzle pieces are addressed in various scientific publications, each with their own perspective. Consequently, a more complete map of the current status and remaining challenges to achieve a better planning of the subsurface is still missing in the scientific literature.

1.2. Aim and scope

Taking a broad international perspective, this paper aims to investigate the subsurface as a multifunctional resource from five focal points: (1) what different professionals mean when using different terms related to the subsurface – a basis for a common language (Section 3); (2) how different professionals describe the subsurface and its multiple resources, functions and services – a basis for common understanding (Section 4); (3) how planning of subsurface use is supported in policy and regulations (Section 5); (4) how the subsurface is included in spatial planning processes (Section 6); (5) what frameworks support decisions on sustainable use of the subsurface (Section 7). The results of this review are discussed in Section 8, and some conclusions drawn from this study are summarised in Section 9.

2. Method and limitations

This review is, with some few exceptions, focused on scientific papers on subsurface use and planning that have various combinations of the following words and concepts in the keywords, abstract and/or title (for detailed search strings see Appendix A): *subsurface, underground space, planning, use, management, confidential information, classified information, secrecy, confidentiality, ownership, property rights, planning law, planning regulation, valuation, economic assessment, classification* and *terminology*. Studies which address in depth only one type of underground resource – e.g. physical space, energy or water – or put the focus on visualisation of any such single resource were considered out of the scope of this paper. The SCOPUS database which was used is relatively comprehensive, having brought to the fore studies from Europe, USA, Canada, Japan, Singapore and China. Furthermore, key contributions from the COST (European Cooperation in Science and Technology) Action "TU 1206: SUB-URBAN – A European network to improve understanding and use of the ground beneath our cities" (Campbell et al., 2017), which brought together members from > 30 European countries, were also reviewed and included in this study, despite not all being found via the SCOPUS database. Also worth mentioning is the special issue of the journal of *Tunnelling and Underground Space Technology* (*TUST*) entitled "Urban Underground Space: A Growing Imperative. Perspectives and Current Research in Planning and Design for Underground Space Use" which collects 35 contributions and provides a state-of-the-art report on underground space research (Bobylev and Sterling, 2016). 21 out of these 35 papers were found relevant for the scope of this study.

A specific limitation of our survey of the literature is that it did not review work on the national registration of subsurface data, digitisation of subsurface data, digitalisation of subsurface data to support decision-making and 3D-modelling of subsurface structures and resources. Despite not being considered for this paper, it should be noted that this research field is currently in a state of rapid development and in the future it is likely to be an important feature in subsurface planning.

3. Terminology

What do scholars actually mean when they refer to, write and talk about the *subsurface*? There are several different terms used in the literature and sometimes these terms mean different things to different authors. Some authors define what they mean with the concepts they are using, and others do not, leaving it to the reader to understand from the context what is meant by certain words or expressions. Table 1 lists terms and concepts used in the reviewed literature. These terms are further highlighted in italics throughout the rest of this text.

The term *use of space* seems to carry different meanings: as a general concept describing the whole underground or as a physical space located underground. *Underground* and *subsurface* mean the same thing, but the terms seem to be used according to distinct traditions in different fields. In engineering, the term *underground* is usually used. Some authors (e.g. ITA, 2019; Evans et al., 2009; Rönkä et al., 1988) refer to a physical space underground when they use the term *underground space,* and e.g. Evans et al. (2009) explicitly include pore space in this concept. However, Bobylev (2016a,b), Makana et al. (2016); Doyle et al. (2016) and Parriaux et al. (2004) include more than the physical space in the concept *underground space*, a "*geospace*" including the physical space, the material itself and the water and energy resource potential. In the latter context, the concept of *Urban Underground Space* (UUS), and the interchangeably used terms *UUS resources, UUS services and UUS functions*, makes sense, where the physical space is only one of several potential *underground resources*.

4. Subsurface as a resource – conceptualisations

Different authors (both individual scholars and research groups) highlight different aspects of the *subsurface* as a resource. Physical space for transports, utilities, subsurface facilities and extraction of ore deposits and industrial minerals has traditionally been the main focus of researchers aiming at facilitating planning, construction and use of this *underground resource* (Table 2). In the 1970s, this conceptual view was broadened to include not only physical space for infrastructure and mining but also for energy, materials and water (Coogan, 1979). In the study by Coogan (1979), the latter three resources are, however, considered as a part of the physical space underground. In contrast, the works by Parriaux et al. (2004) and Admiraal and Cornaro (2016a) highlight four *underground resources* as separate domains of the *subsurface*, i.e. stratum underground, whereas artificially or naturally created physical space is only one part of a whole (Fig. 1). Such division of the *subsurface* is most common in scientific literature representing the field of engineering (see e.g. Doyle et al., 2016; Parriaux et al., 2004, 2007).

Parriaux et al. (2004) identify the following resources as part of *underground*: (a) physical space resources (urban systems and structures); (b) water resources (underground water aquifers); (c) geomaterials (extraction and use for city development); (d) geothermal resources; and (e) heritage (cultural heritage and archaeology). Admittedly, Coogan (1979) and Winqvist and Mellgren (1988) also acknowledge cultural heritage underground but rather as part of the physical space. Based on the study by Parriaux et al. (2004); Admiraal (2006) specifies the following *UUS* uses: (1) transport (high pressure transport pipelines and utility networks, tunnels for transportation); (2) production (subsurface biodiversity, foundations for nature, agriculture and city parks, exploration of natural resources, water reservoirs and water extraction); (3) urban structures (foundations and structures for roads and buildings, car parking, underground stations, cinemas, offices, shopping centres, housing); (4) storage (storage of waste and dangerous goods, decontamination and clean-up of contaminated sites, thermal energy storage, gas storage, storage of carbon dioxide); (5) archival repository (cultural heritage and archaeology, geomorphologic and earth science values, subsurface biodiversity).

Using the *ecosystem service* (*ESS)* concept as a starting point, Bobylev (2009) further broadens the engineering view on the *subsurface* as a resource and introduces *UUS services* (Fig. 2). Similar to the studies by Parriaux et al. (2004) and Admiraal (2006), cultural heritage is considered as an important resource. Bobylev (2009) also adds the component of life-support systems, i.e. groundwater as supply to surface vegetation. Sterling et al. (2012) elaborate the study by Bobylev (2009) indicating geothermal energy as either renewable or non-renewable depending on the extraction rate compared to the ability of the ground thermal field to be replenished.

Depending on various uses of the *subsurface* and two subsurface depths (shallow and deep), Griffioen et al. (2014) specify *subsurface functions* which include: space and underground constructions; geomaterials, e.g. sand and gravel, including contaminated soils; extraction of gas and salt; extraction of drinking water; and storage of aquifer thermal and geothermal energy, carbon dioxide and radioactive waste (Fig. 3).

De Mulder and Pereira (2009) introduce the term *geoassets* to stress the value of the renewable and non-renewable *underground resources* – i.e. soil, water, minerals, energy and physical space – to society. De Mulder et al. (2012) define seven classes of *subsurface functions* in the context of *ESS*: (1) source of natural resources; (2) storage of material (solid, liquid, gas); (3) space for public and commercial use; (4) space for infrastructure; (5) medium for foundation of constructions; (6) component in life-support systems; and (7) archive of historical and geological heritage.

Gray (2012) and Gray et al. (2013) present another way to describe the *subsurface* as a resource by considering *abiotic ESS*, also called by the authors *geosystem services* provided by the geosystem (Fig. 4). Here, geodiversity underpins delivery of these services. Gray (2012) emphasises supporting *soil services*, which: (1) act as a habitat for soil biota and as a gene reserve; (2) filter and bind substances from water and receive particulates from the atmosphere; (3) act as a storage of water and carbon and recycler of organic matter; (4) support ecological habitat and biodiversity; (5) regulate the flow of water from rainfall to watercourses, aquifers, vegetation and the atmosphere; (6) act as a

Table 1
List of terms and definitions sorted from more general to more specific.

Term/concept	Definition/meaning/interpretation	Reference/comment
Space	The dimensions of height, depth and width within which all things exist and move. A concept.	Oxford dictionary https://en.oxforddictionaries.com/definition/space
Physical space (apart from space as a general concept)	Possible to measure what separates one point from another. A specific extension of the three-dimensional region (which in principle is measurable).	Dassonville, 2017 Interpretation.
Stratum (*plural:* strata)	A layer or a series of layers of rock in the ground.	Oxford dictionary https://en.oxforddictionaries.com/definition/stratum
Ground	Includes the surface of the land and its geological subsurface.	Price et al., 2016
Subsurface	Underground, beneath the surface.	International Tunnelling and Underground Space Association's (ITA's) Glossary https://tunnel.ita-aites.org/en/component/seoglossary/1-main-glossary
	The stratum or strata below the earth's surface.	Oxford dictionary https://en.oxforddictionaries.com/definition/subsurface
	Everything below ground level.	Maring and Blauw, 2018
Geological subsurface	Referring to the natural (not man-made) subsurface, in relation to its potential to store different items (e.g. water, energy, carbon dioxide, hydrogen, air).	Bauer et al., 2013 Interpretation.
Underground land	Relates to the physical space underground, or "subsurface estates" – in the context of valuing land.	Pasqual and Riera, 2005 Interpretation.
Underground	Below ground level.	ITA's Glossary https://tunnel.ita-aites.org/en/component/seoglossary/1-main-glossary
Underground space	A (physical) space created or used underground.	
	A (physical) space below ground level.	Rönkä et al., 1998
Underground space, subsurface space	Refers to any (physical) space that is below ground level. Caves, man-made spaces and pore space.	Evans et al., 2009 Interpretation.
Urban Underground Space (UUS)	A geo space beneath urban areas, including wider areas of UUS that provide direct services to a city, e.g. groundwater supply or geothermal energy. UUS encompasses geologically formed rocks and soils, and artificial spaces, as well as caverns of various origins.	Bobylev, 2016a,b, Makana et al., 2016
Urban volume	Potential (physical) space, groundwater, geothermal energy and geomaterials.	Doyle et al., 2016
Underground resources	Geomaterials, water, geothermal energy, (physical) space.	Doyle, 2016
Urban underground resources	(Physical) space, geomaterials, groundwater, geomaterial energy, cultural heritage.	Parriaux et al., 2004
Urban Underground Space (UUS) resources	(Physical) space, geomaterials, groundwater, geothermal energy.	Parriaux et al., 2007
Urban Underground Space (UUS) services/resources	*Non-renewable*: physical space, space continuum that has certain soil strength properties, excavated materials and cultural heritage; *Renewable*: groundwater (supply for drinking, surface vegetation, surface water bodies) and geothermal energy.	Bobylev, 2009
Urban Underground Space (UUS) services (*or UUS functions*)	Storage; industry; energy production; transport; utility supply; waste disposal; provision of public space and private space.	Bobylev, 2016a,b
Subsurface functions	(Physical) space and underground construction, materials (sand, gravel including contaminated soil), storage of aquifer and geothermal energy storage, storage of CO_2 and radioactive waste, extraction of gas and salt.	Griffioen et al., 2014
Subsurface qualities (*ondergrond-kwaliteiten* in Dutch)	A subdivision that relates to common categorisations of ecosystem services of the subsurface into four main types of qualities that should be considered and managed in relation to spatial planning: producing, regulating, carrying and informative qualities.	Hooimeijer and Maring, 2013; Tummers and Hooimeijer, 2016
Geoasset	The beneficial function provided by the ground (surface and geological subsurface) as a consequence of its properties and the process that operate within it. The beneficial functions include benefits to society or the environment.	de Mulder and Pereira, 2009; Price et al., 2016
Urban Underground Infrastructure (UUI)	A set of artificial structures included in UUS and located entirely or partially below ground level, interconnected physically or functionally. UUI is represented by a variety of utilities, rail and motor tunnels, buildings' basements used as storages, garages, public pedestrian and shopping zones, etc.	Bobylev, 2016a,b
Subsurface/ underground planning	Planning activity aiming to divide subsurface for human activities according to the ecological, economic and technical point of view.	ITA's Glossary https://tunnel.ita-aites.org/en/component/seoglossary/1-main-glossary
Subsurface mapping	Mapping of subsurface spaces (results of underground human activities) from various points of view (location, dimensions, geological conditions, environmental impact, actual technical state, reusing possibilities, etc.).	
Ecosystem services (ESS)	ESS are benefits that humans directly or indirectly gain from ecosystems and which yield wellbeing. ESS are classified into four categories: provisioning, regulating, cultural and supporting. Supporting ESS underpins delivery of all other ESS.	MEA, 2005
	Biodiversity has a crucial role in delivery of ESS. Service of nature is classified as ESS only if they involve biotic components or biological processes.	TEEB, 2010; CICES, 2018
Soil services	ESS supplied by soils.	Gray, 2012
Geosystem services		Gray, 2012; Gray et al., 2013

(*continued on next page*)

Table 1 (*continued*)

Term/concept	Definition/meaning/interpretation	Reference/comment
	Geodiversity has a crucial role for delivery of abiotic ESS which are essential for human wellbeing but excluded from the ESS classification frameworks.	
	Geosystem services are benefits that humans directly or indirectly gain from geosystems and which yield wellbeing, here both biotic and abiotic.	van Ree et al., 2017
Soil	A mixture of weathered rock debris and organic matter, organised into the structured layers of a soil profile.	Gray, 2012
Pedosphere	The earth's soil layer.	Oxford dictionary https://en.oxforddictionaries.com/definition/pedosphere
	The pedosphere is the outermost layer of the earth that is composed of soil and subject to soil formation processes. It develops when there is a dynamic interaction between the atmosphere (air in and above the soil), biosphere (living organisms), lithosphere (unconsolidated regolith and consolidated bedrock) and the hydrosphere (water in, on and below the soil).	Wikipedia https://en.wikipedia.org/wiki/Pedosphere (2019-05-31)
	The transition zone between ecosystem services and geosystem services. The vast majority of species (invertebrates, fungi and bacteria) lives in the pedosphere. The strong decline in biological activity below this soil zone delineates the boundary between delivery of ecosystem services and geosystem services.	van Ree et al., 2017

growing medium and nutrient supply for food, timber and energy crops and the basis for livestock production; and (7) act, in effect, as environmental archives.

The work by van Ree and van Beukering (2016) makes a distinction between stocks (e.g. structure, mineral resources, stability) and flows of services (linked to geological, energy and material cycles) arising from these stocks. The authors argue that *ESS* is only a small part of services provided by the earth system, where the *geosystem services* are crucial for promoting human wellbeing but usually excluded from *ESS* classification frameworks (van Ree and van Beukering, 2016). This view is supported by van der Meulen et al. (2016b), who argue that abiotic flows should be included as an inherent part of classifications such as the Common International Classification of Ecosystem Services (CICES), to make the application of the *ESS* concept more holistic. Further, the study by van Ree et al. (2017) elaborates the notion of *geosystem services* to include the representation of goods and services from the *subsurface*, based on the concept introduced by Gray (2012) and Gray et al. (2013) as well as *subsurface functions* described by de Mulder et al. (2012) (Fig. 5). These *geosystem services* (here, both biotic and abiotic) are seen to be complementary to the categorisation of *ESS* defined under CICES (2012). Van Ree et al. (2017) suggest that the distinguishing criterion between *ESS* and *geosystem services* is the depth from which the services are obtained, i.e. the pedosphere forms a transition zone between the two types of services while the boundary is delineated by the strong decline in biological activity below this zone.

Tummers and Hooimeijer (2016) highlight *subsurface qualities* from a planning perspective, dividing them into four categories: carrying, information, regulating and production qualities (Fig. 6). Hooimeijer and Maring (2018) group these *subsurface qualities* into four broad planning themes in an effort to approach and communicate with the field of engineering: (1) civil constructions (the carrying capacity, stability of soil, underground space technology, archaeology, cables and pipes, and unexploded ordnance); (2) energy (Underground or Aquifer Thermal Energy Storage (UTES, ATES), geothermal energy and oil, gas or shale gas fossil energy); (3) water (drinking water, water filtering, water storing); (4) soil (healthy and clean soil, living soil, crop production capacity, geomorphological diversity, landscape diversity, ecological diversity, source of minerals, storage of materials and CO_2 storage capacity).

5. Subsurface in policy and legislation

Because national territories are normally made up of property units of public or private ownership, which are delimited by surface boundaries, it is important, in respect to subsurface utilisation or preservation, to define how property rights extend downwards. The most common principle of property law is the Latin maxim *Cuius est solum, eius est usque ad coelum et ad inferos* which means that "The owner of the surface also owns to the sky and to the depths" (Thomas, 1979, 1981; Barker, 1991; Sprankling, 2008; Morgan, 2013). For more detailed explanations on this Latin maxim, the reader is referred to Sprankling (2008); however, here it is sufficient to note that in principle this means that the landowner owns the *subsurface* down to the earth's centre if a depth limit is not specified in law, e.g. as in Norway, Sweden, the Netherlands and USA (Table 3). However, the rights of use can be restricted upwards, e.g. to permit communication by air routes, and downwards, e.g. to permit use of the *subsurface* for tunnels, cables and pipes by the state or third parties. The former implies that the upper stratum above a certain height limit is regarded as part of the public domain. The latter is usually achieved through (*i*) easements, i.e. the right to use someone else's property without possessing it, and/or (*ii*) 3D properties (Clarke,

Table 2
Subsurface as physical space and source of minerals by the International Tunnelling and Underground Space Association (ITA) (ITA, 2019).

Category	Description
Transport in urban and interurban environments	Urban road tunnels, railway tunnels, tunnels for mass transit transportation, pedestrian tunnels, tunnels for transport of goods, underground parking, underground railway and mass transit stations, navigation canals.
Urban utilities	Underground pneumatic waste, water supply and storage, sewerage (including underground treatment plants), flood control systems, multi-purpose gallery, urban heating/cooling systems, electrical and communication cables.
Non-urban utilities	Energy transport (high voltage electricity cables, oil ducts, gas ducts), hydropower underground stations and tunnels, water transfer tunnels, nuclear waste storage, hydrocarbon storage (caverns for storage of oil and gas).
Subsurface facilities	Public buildings, goods storage, industrial facilities, military facilities.
Mining	Excavation of underground tunnels, shafts, galleries and caverns for ore extraction.

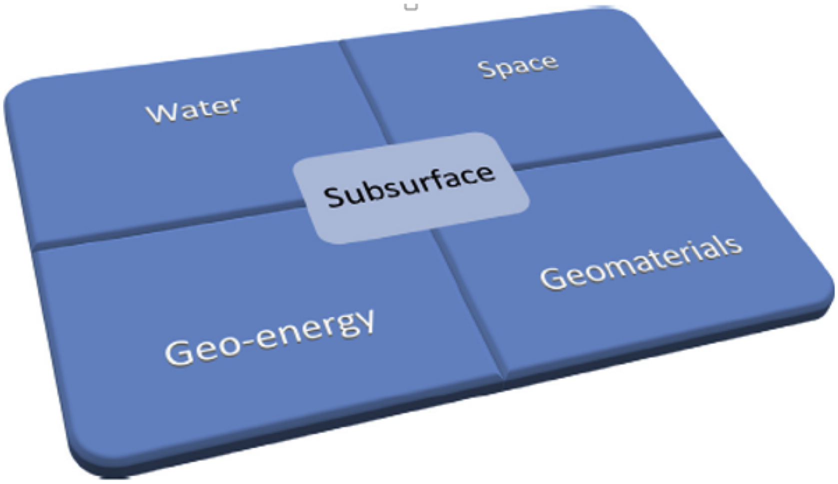


Fig. 1. A model of the subsurface as comprising four exploitable resources (Admiraal and Cornaro, 2016a).

2000). The laws related to property rights serve as an important instrument for plan realisation (Norrman et al., 2015b).

In contrast, planning laws are usually a set of rules that are created and enforced through relevant institutions to regulate spatial planning and to achieve a balance between public and private interests with respect to land use. As early as 1975, at the inaugural annual meeting of the International Tunnelling and Underground Space Association (ITA), the term *subsurface planning* was introduced (Jansson, 1976). A pioneering Swedish study that was already ongoing at that point, aimed at providing the basis for legal regulations on responsibility for planning of subsurface use in spatial planning processes (Jansson and Winqvist, 1977), and in the past 40 years a great deal of additional work has been done to construct appropriate legal frameworks for *subsurface planning* (e.g. ITA, 1991; Barker, 1991; Navrvi et al., 1994; Clarke, 2000; Takasaki et al., 2000; Liu et al., 2005; Lamé and Maring, 2014; Norrman et al., 2015b; Ikävalko et al., 2016; Kishii, 2016; Laursen and Mielby, 2016; Qihu, 2016; Seither et al., 2016; van Ree and van Beukering, 2016; Vähäaho, 2016, 2018; von der Tann et al., 2018; Whitbread et al., 2016; Zammit, 2016; Zhou and Zhao, 2016; Hooimeijer and Tummers, 2017). Along with knowledge exchange in spatial planning processes, development of relevant policies is critical for managing the risks and opportunities presented by the *subsurface* as well as maximising its economic, social and environmental benefits (Dick et al., 2019).

Despite the obvious importance of the subject, information on treatment of the subsurface in policy and legislation worldwide is scarce, at least in the literature sources considered here. Two surveys carried out by ITA (Barker, 1991; Clarke, 2000) to examine international legislation on the subsurface are now almost 20 and 30 years old, respectively. Further, the information that is to be found in the contemporary literature is fragmented. For example, it is unclear in the reviewed studies (Vähäaho, 2016, 2018; Ikävalko et al., 2016; Zammit, 2016) if: (i) easements have to be formed for underground constructions carried out in the public interest in Finland and Norway; and (ii) private land lots on Malta shall be acquired to permit use of the *subsurface* in the public interest. Without claiming to be exhaustive, an international overview of regulations on *subsurface planning* and property rights to the *subsurface* is presented in Table 3.

Sprankling (2008) summarises the four alternative models of subsurface ownership thus: (1) ownership down to the centre of the earth;

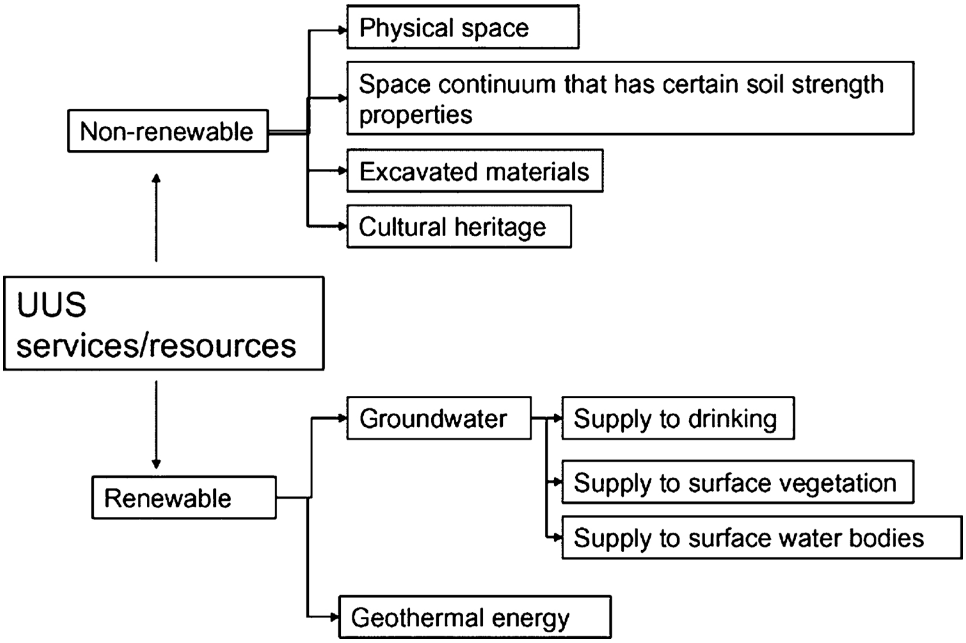


Fig. 2. Classification of urban underground space services (Bobylev, 2009).

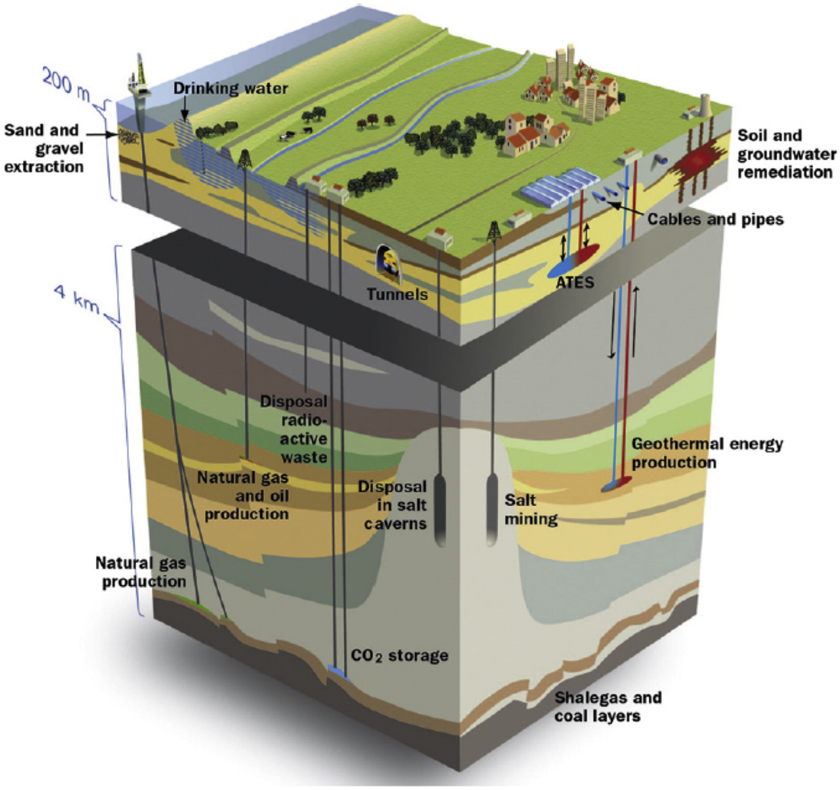


Fig. 3. Multiple functions of the subsurface (Griffioen et al., 2014).

(2) ownership based on first-in-time exploitative use; (3) ownership for reasonable and foreseeable uses – access to the resources in the *subsurface* can be acquired by the first-in-time stranger if the property owner does not claim her right of reasonable use first; and (4) ownership to a specified depth limit. In some states in the USA the first-in-time stranger – the (2) and (3) models – can capture access to the resources in the *subsurface* of other corresponding property units, adopted as the English common law rule of capture (Sprankling, 2008). Sprankling (2008) stresses that this rule facilitates destruction and overexploitation of natural resources. To protect owners of corresponding property units from damages, another Latin maxim, namely *Sic utere tuo, ut alienum non laedas* which means “Use your own property so as not to injure that of another”, is applied to utilisation of *underground resources* in the USA (Ibid.).

As shown in Table 3, the depth limits are usually used to address (I) private ownership of the subsurface (Singapore), (II) use rights to the subsurface by private landowners (Japan, Finland and Norway) or (III) ownership of such *underground resources* as minerals, oil and gas by the state (Denmark and the Netherlands). The former two are aimed at facilitating the use of physical space underground in the public interest (Kishii, 2016; Vähäaho, 2016; Zhou and Zhao, 2016), whereas the latter is aimed to protect property rights of the state (or the Crown) to *underground resources*. Note that a depth limit of “reasonable use” in Norway (Table 3) is used to specify the extent of ownership rights, which is different from ownership for reasonable use as defined by Sprankling (2008).

So far, regulations on *subsurface planning* are enforced in Finland only (Vähäaho, 2016, 2018). The Land Use and Building Act stipulates planning of the *subsurface* as follows: “If detailed planning of land use is necessary only for the construction or other use of underground spaces, the detailed plan may also be developed in stages so that it covers only underground areas. In an area where the detailed plan covers only underground spaces, the provisions of this Act or other laws which apply to areas that lack a detailed plan and which govern the land use aboveground are applied” (§56, the Land Use and Building Act of Finland; translation to English by the authors).

Further, regulations on *subsurface planning* are under development in the Netherlands (NL, 2019). The upcoming Environment and Planning Act is aimed to facilitate urban development bringing the *subsurface* to a special focus, while also combining 15 separate environmental laws into one act (Lamé and Maring, 2014). The ambitions for sustainable use of the *subsurface* in the spatial planning processes were formulated in a covenant of 2016 between the Dutch government, provinces, municipalities and water authorities. The covenant addresses different *subsurface functions* and uses, e.g. cables and pipes, natural resources and geothermal energy. Furthermore, the Dutch government has been developing a national “Subsurface Policy Strategy” (STRONG) to promote sustainable use of the *subsurface*.

Some fairly recent initiatives on subsurface data collection have been launched in the UK and the Netherlands to assist in spatial planning processes. In 2012, the British Geological Survey in collaboration with Glasgow City Council developed the “Assessing Subsurface Knowledge” (ASK) network for collecting and making accessible environmental and engineering geoscience data (Whitbread et al., 2016; von der Tann et al., 2018). Arising through voluntary agreements, partnerships and collaboration, planning policy for Glasgow explicitly recognises the environmental and economic value of the *subsurface* and “reflects the importance of the subsurface environment for the health, wealth and growth of the city” (Dick et al., 2019). Data on the subsurface is voluntarily donated by industry and national stakeholders in the UK (Ibid.). Under pioneering legislation, in 2015, in the Netherlands, the baseline underground register *Basisregistratie Ondergrond* (BRO) was established “to consolidate geological and exploration data as well as data about mining activities and the associated structural assets” (Campbell et al., 2017; von der Tann, 2018). In contrast to ASK, contributions to BRO are mandatory (Campbell et al., 2017).

6. Subsurface planning

The increase in the world’s urban population from 7% in the 1800s

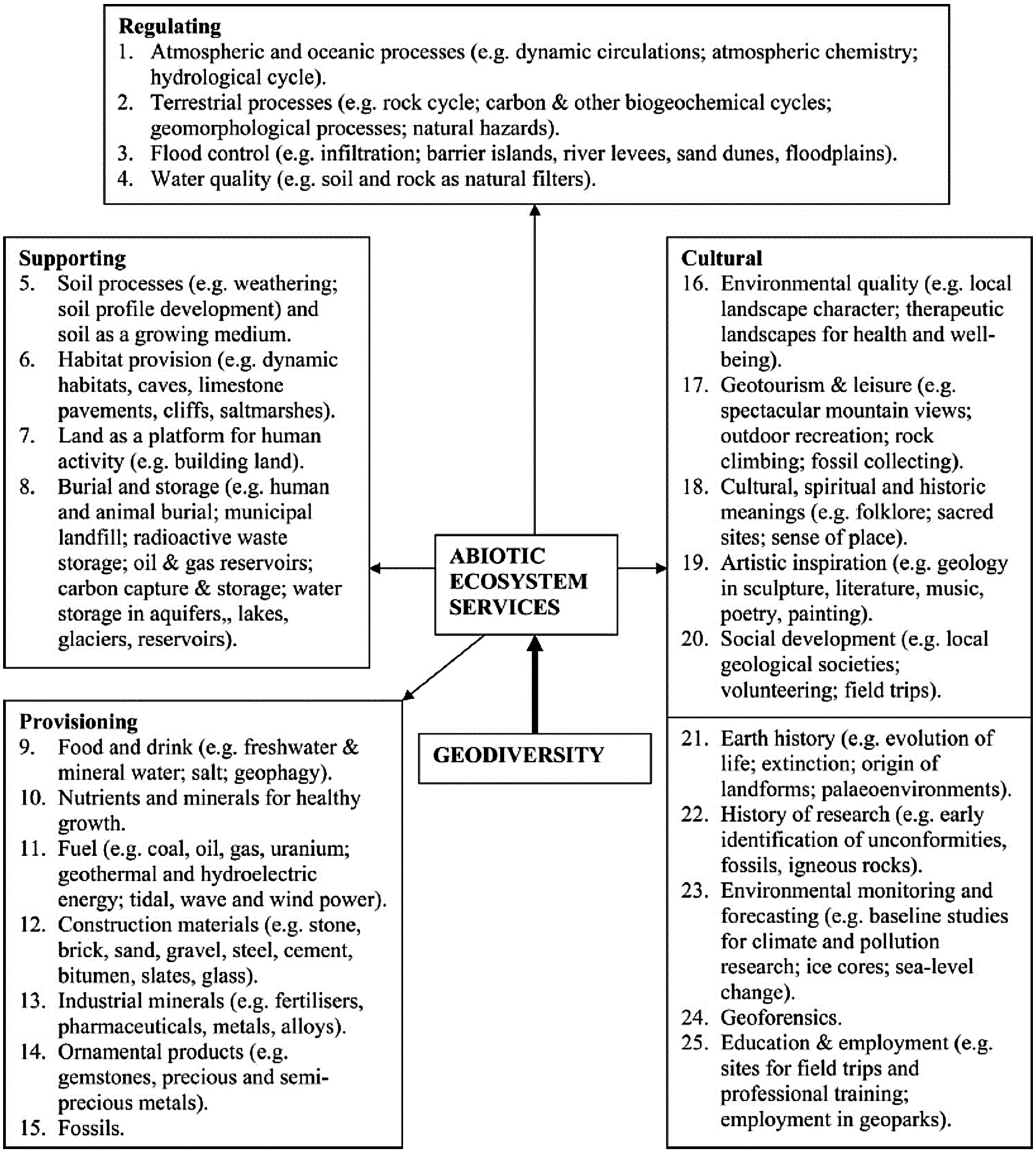
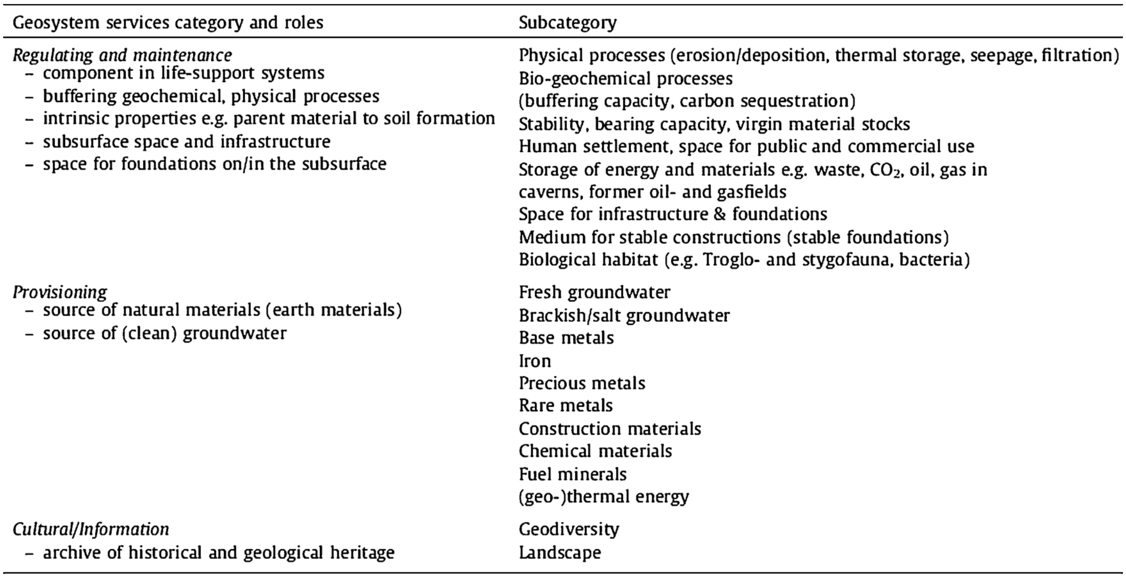


Fig. 4. Abiotic ecosystem services provided by the geosystem (Gray, 2012; Gray et al., 2013).

to 16% in the 1900s (Ritchie and Roser, 2019) and the emerging demands for housing resulted in dense and disorganised spatial expansion of cities and a number of consequent problems (EC, 1997). This situation called for the establishment of the spatial planning systems in the 1900s across most European countries to ensure – through the control of the state – physical improvement of urban areas (Ibid.). The pioneers of *underground space* research, Hénard (1910) and Webster (1914), had early on suggested a subdivision of the *UUS* under streets into different levels for utilities, i.e. cables and pipes, and transport of people and goods (see e.g. Fig. 7), in order to improve quality of life and wellbeing of inhabitants in cities. Further, the French architect Edouard Utudjian defined the concept of "*Urbanisme souterrian*" in the 1930s, i.e. underground urbanism, which was an (too) early idea of *subsurface planning* (Besner, 2016; Duffaut, 2006; von der Tann et al., 2019). Unfortunately, the concept and the underground urbanism movement died with their founder in 1975 (Besner, 2016; von der Tann et al., 2019).

In 1970 (as clarified by Janssen (1976)), in response to the perceived deficiency of interest in and experiences of underground space use, the Organisation for Economic Co-operation and Development (OECD) – founded in 1961 to stimulate economic progress and world trade among 20 member countries – brought together its member nations for an advisory conference on tunnelling. This event led to the establishment of the ITA in 1974 for promoting a rational use of *underground space* and stimulating research and development on tunnelling. *Subsurface planning* became one of the ITA's research and development topics to make planning of subsurface use an integral part of spatial planning (Ibid.). Similar ideas are promoted by the Associated Research Centers for Urban Underground Space (ACUUS), which was launched in 1996. For a comprehensive historic overview of *UUS* inclusion in spatial planning in the 20th century, the reader is referred to the study by von der Tann et al. (2019).

The inventory of good spatial planning practices in European countries reveals that a systematic approach to inclusion of the *subsurface* into spatial planning processes at a city-scale is, almost without exception, missing (Mielby et al., 2017a). Historically, the *subsurface* has been used without any real planning as a rapid solution for "a



Geosystem services category and roles	Subcategory
Regulating and maintenance – component in life-support systems – buffering geochemical, physical processes – intrinsic properties e.g. parent material to soil formation – subsurface space and infrastructure – space for foundations on/in the subsurface	Physical processes (erosion/deposition, thermal storage, seepage, filtration) Bio-geochemical processes (buffering capacity, carbon sequestration) Stability, bearing capacity, virgin material stocks Human settlement, space for public and commercial use Storage of energy and materials e.g. waste, CO_2, oil, gas in caverns, former oil- and gasfields Space for infrastructure & foundations Medium for stable constructions (stable foundations) Biological habitat (e.g. Troglo- and stygofauna, bacteria)
Provisioning – source of natural materials (earth materials) – source of (clean) groundwater	Fresh groundwater Brackish/salt groundwater Base metals Iron Precious metals Rare metals Construction materials Chemical materials Fuel minerals (geo-)thermal energy
Cultural/Information – archive of historical and geological heritage	Geodiversity Landscape

Fig. 5. Geosystem services for sustainable use of the subsurface (van Ree et al., 2017).

problem on the ground by moving it underground" (Parriax et al., 2004), or for "the shortage of space above ground" (Admiraal, 2006). A general trend in Europe and beyond is that the *subsurface* has, for a long time, not been taken into consideration in spatial planning processes until the plan realisation phase is reached (Norrman et al., 2016; Mielby et al., 2017a; Dick et al., 2019). This inevitably leads to lost opportunities because most of the benefits are obtained through an integral consideration of the *subsurface* in the early phases of a spatial planning process (Uršej and Kontić, 2007; Norrman et al., 2016; Dick et al., 2019). Sectoral planning – i.e. disintegrated consideration of underground resources one by one to serve one specific need at a given time (Blunier et al., 2007) – is usually the case (Parriaux et al., 2007; Mielby et al., 2017a, b; von der Tann et al., 2018, 2019; Dick et al., 2019). Admiraal (2006) emphasises that careful *subsurface planning* opens the opportunities for synergies between the different types of utilisation of the *subsurface*, providing examples of the Kuala Lumpur SMART tunnel which combines storm water management and transport, and the combination of transport infrastructure and geothermal energy.

Nowadays, the old idea of *subsurface* subdivision into different layers is still found to be a feasible solution for planning of a rational use of the *UUS* in several countries, e.g. Japan (Kishii, 2016; Stones and Heng, 2016), Singapore (Zhou and Zhao, 2016), the Netherlands (Griffioen et al., 2014; Admiraal and Cornaro, 2016a) and China (Stones and Heng, 2016). These efforts are aimed at producing *Underground Master Plans* at a city level. In accordance with Delmastro et al. (2016), an *Underground Master Plan* should contain:

- facilities projects and tunnels (existing and future);
- space reservations (existing and future);
- existing secure access links to technical maintenance facilities/tunnels;
- new locations for various functions;

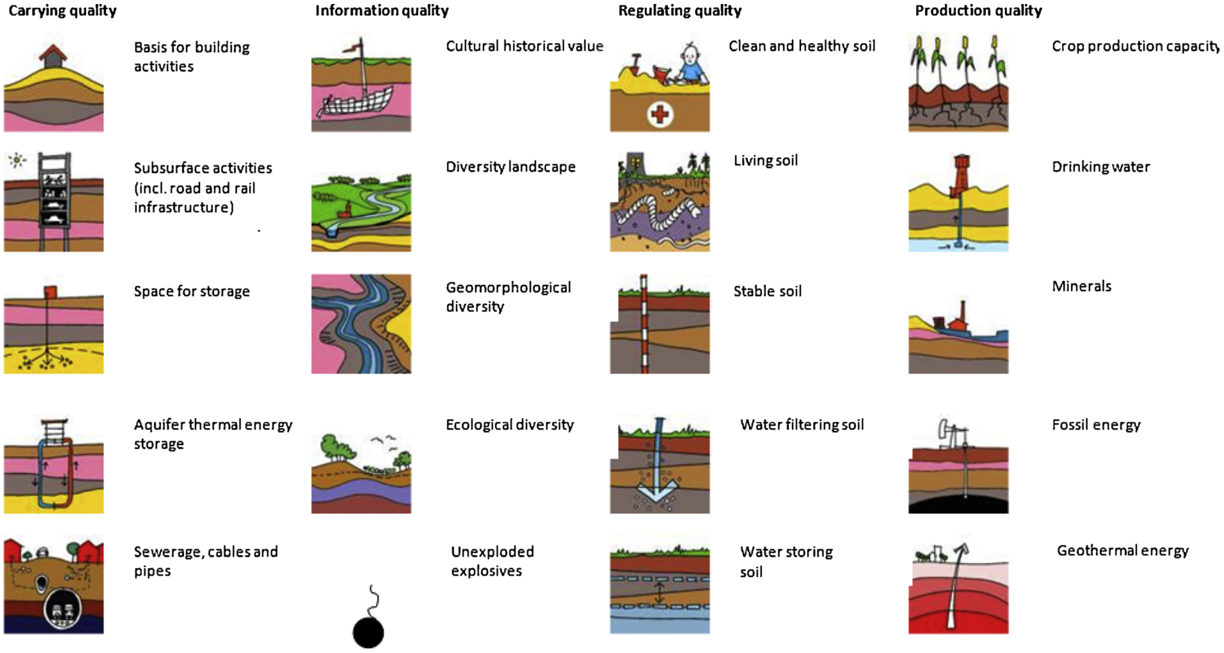


Fig. 6. Qualities of the subsurface (Hooimeijer and Maring, 2013, 2018; Tummers and Hooimeijer, 2016; Ruimtexmilieu, 2019).

Table 3
An international overview of regulations on subsurface planning and property rights to the subsurface.

Country (reference)	Property rights			Regulations
	Specified depths	Ownership	Right of use	
China (Barker, 1991; Liu et al., 2005; Qihu, 2016; Zhao et al., 2016; Zhang et al., 2017)	Not specified in law.	Land is under public ownership. The state owns urban land, the subsurface and its resources.	In 2007, amendments to property law introduced land use rights to 3D properties (constructions) underground.	The urban and rural planning law of 2008 stipulates that UUS development and utilisation of UUS should comply with the principle of spatial planning, comprehensive development and rational utilisation. No legally binding and unified regulations or specifications on development and utilisation of USS. There are some rules on underground space development dating from 1997, amended in 2011.
Denmark (Barker, 1991; Laursen and Mielby, 2016)	250 m, specified in law.	Private land lots shall be acquired for use of the shallow subsurface (0–250 m) in public interests. Geomaterials found in the shallow subsurface are owned by landowners. Minerals, oil and gas below a specified depth limit are owned by the state.	Land owner's use rights of the subsurface are limited to a specified depth limit.	No regulation on subsurface planning. Regulations apply to use of geomaterials and extraction of groundwater.
Finland (Navrvi et al., 1994; Barker, 1991; Clarke, 2000; Vähäaho, 2016, 2018; Ikävalko et al., 2016; Land Code of Finland)	6 m (where building foundations are not generally built), not specified in law.	The extent of ownership rights is not specified in law, i.e. to the centre of the earth.	Land owner's use rights of the subsurface are limited to a depth limit of 6 m. Special building permits are required for use rights and thus building activities below a specified depth limit.	Subsurface planning is regulated by the Land Use and Building Act. The Underground Master Plan of Helsinki has been legally binding since 2010. Special regulations on Environmental Impact Assessment (EIA) of future underground constructions.
Japan (Barker, 1991; Kishii, 2016; JP, 2019)	40 m (where basements are typically not constructed) or 10 m (where building foundations are not generally built), specified in law.	The extent of ownership rights is not specified in law, i.e. to the centre of the earth.	Private land ownership rights do not include use rights to the deep underground (lower than specified limits). The existing subways, roads, railways, water pipes, supply and disposal facilities are mainly located in the shallow subsurface (0–40 m) under public land lots.	The Act on Special Measures concerning Use of Deep Underground came into force in 2001. This Act only applies to the three metropolitan regions of Tokyo, Osaka and Nagoya.
Norway Barker, 1991; Seither et al., 2016; Dick et al., 2019)	Depth of "reasonable use", not specified in law.	The extent of ownership rights is not specified in law, i.e. to the centre of the earth. Oil and gas are owned by the state.	No land owner`s permission is needed for use of the subsurface for public constructions below a depth of "reasonable use".	No regulation on subsurface planning or property rights delineation by depth in law. Approval is not needed for energy (100–300 m down) or groundwater well installation by site owners. Regulations on EIA of future constructions.
Malta (Zammit, 2016)	Not specified in law.	The extent of ownership rights is not specified in law, i.e. the centre of the earth.	Use of the subsurface for public constructions requires approval from a relevant institution.	No regulation on subsurface planning. Property rights and land acquisition in public interests are regulated by Civil Code and Land Acquisition Ordinance, respectively.
Singapore (Zhou and Zhao, 2016; Stones and Heng, 2016)	30 m below the legally defined Singapore Height Datum, specified in law.	Limitation of ownership rights below a specified depth limit.	Not specified in the paper.	Laws on property rights and land acquisition, amended with respect to the subsurface in 2015.
Spain (van der Meulen et al., 2016b)	Not specified in law.	Not specified in the paper.	Not specified in the paper.	No regulation on subsurface planning or property rights delineation by depth in law.
Sweden (Victorin, 2000; Norrman et al., 2015b; Hooimeijer and Tummers, 2017)	Not specified in law.	The extent of ownership rights is not specified in law, i.e. to the centre of earth. The state can declare national interest for a certain area and restrict exploitation of its *underground resources*.	Land owner's use rights of the subsurface are not limited with depth. Easements or 3D properties are formed for use of the subsurface under private land lots for underground constructions by the state, e.g. tunnels, or third parties, e.g. cables and pipes. Capture rule (see explanation in the text) applies to extraction of minerals and peat.	No regulation on subsurface planning or property rights delineation by depth in law. Special regulations apply to use of subsurface for extraction of minerals, peat, groundwater and geothermal energy. No permission is needed for extraction of groundwater by single family dwellings (the Water Enterprises Act of 1998). Permission is required for installation of wells for extraction of geothermal energy. All wells are registered in the Well Archive (Brunnsarkivet in Swedish), which is maintained by the Swedish

(*continued on next page*)

Table 3 (*continued*)

Country (reference)	Property rights			Regulations
	Specified depths	Ownership	Right of use	
				Geological Survey. Special regulations on EIA of future underground constructions.
The Netherlands (Lamé and Maring, 2014; van der Meulen et al., 2016b; Norrman et al., 2015b; Hooimeijer and Tummers, 2017; NL, NL, 2019)	100 m or 500 m, specified in law.	The extent of ownership rights is not specified in law, i.e. to the centre of earth. The state owns oil, gas and minerals below a depth limit of 100 m.	Easements are formed for use of the subsurface under private land lots for underground constructions by the state, e.g. tunnels, or by private/state companies, e.g. cables and pipes.	Subsurface planning will be regulated by the upcoming Environment and Planning Act, which will combine 15 environmental laws into one act, planned to come into force in 2021. A covenant (commenced in 2016) between the Dutch government, provinces, municipalities and water authorities ensures sustainable use of the subsurface. Special regulations apply to geothermal energy extraction below 500 m.
UK (Morgan, 2013; Whitbread et al., 2016; Stones and Heng, 2016; von der Tann et al., 2018; Price et al., 2018; Dick et al., 2019)	200 m, specified in law.	The extent of ownership rights is not specified in law, i.e. to the centre of earth. The Crown owns oil, gas and minerals.	No land owner`s permission is needed for use of the subsurface for shale gas extraction below a specified depth limit.	No regulations on subsurface planning. Predominance of ecological and regulatory institutions in governance of the subsurface in the spatial planning processes. The environmental regulations which concern the subsurface stem from EU Directives, e.g. Urban Waste Water Treatment, Water Framework, Extractive Waste, Groundwater, Infrastructure Information in the EC, Flood, Waste Framework, Renewable Energy. There is no regulation of thermal energy extraction.
USA (Sprankling, 2008; Morgan, 2013)	Not specified in law.	The extent of ownership rights is not specified in law, i.e. the centre of the earth principle is usually applied. The first-in-time user owns oil, gas and minerals under her property unit and in the whole vein.	No land owner`s permission is needed for use of the subsurface for gas, oil and mineral extraction as well as waste disposal.	No information on regulations with respect to subsurface planning in the reviewed papers. Special regulations apply for extraction of groundwater, gas, oil, minerals and the disposal of waste underground, but differ between the states. There are three main approaches to groundwater ownership: (1) reasonable use; (2) permit; or (3) correlative rights.

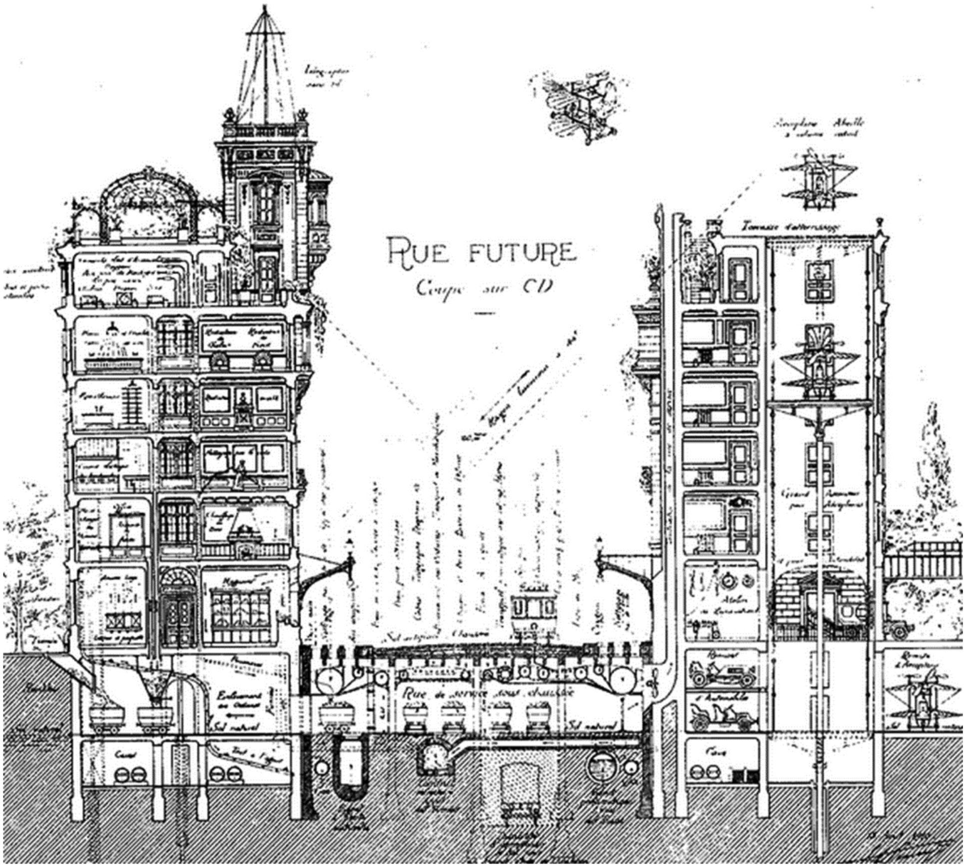


Fig. 7. The plan of a street in Paris of average importance by Hénard (1910). Underground is divided into different levels for utilities and transport of people and goods.

- engineering requirements and guidelines.

Zargarian et al. (2013) list a number of challenges to including *UUS* and associated sustainability issues into a master plan: lack of knowledge about *UUS*, lack of 3D planning, misconceptions about *underground resources* and anticipating uncertain futures by developing scenarios.

An actual *Underground Master Plan* has, so far, only been produced for the city of Helsinki, Finland (Vähäaho, 2016; Delmastro et al., 2016). This legally binding plan contains space reservations for transport, civil defence, sports, various installations and establishments, water and energy supply, parking, storage, waste management and similar. An *Underground Master Plan* for the city-state of Singapore is currently under development, aiming at: (1) mapping existing and planned underground uses; (2) identifying and reserving underground space for future developments; (3) ensuring that underground and aboveground spaces are synergised in the development process (Zhou and Zhao, 2016).

In China, the topic of *UUS* had been included in the *Master Plan* for the city of Hangzhou, drafted in 1993. In 2004, the stratification-based *Master Plan* for *UUS* development and utilisation was created for the city of Beijing (Zhao et al., 2016), and this was quickly followed in 2005 by the *Shanghai Underground Space Concept Plan* (Delmastro et al., 2016). In 2007, the stratification-based *Master Plan* for *UUS* development and utilisation was also developed for the city of Shanghai (Stones and Heng, 2016). In the period 2006–2014, *subsurface planning* was integrated into broader planning processes for the cities of Shenzhen, Xiamen, Shenyang, Nanjing, Bengbu, Qingdao, Hefei, Linyi and Tongren (Zhao et al., 2016). Delmastro et al. (2016) classify the Chinese *Master Plans* for *UUS* development as sectoral.

German examples of first implementations steps of *subsurface planning* are (1) the regional development programme of Mecklenburg-Western Pomerania, where the *subsurface* is treated in a separate chapter, and (2) the state of Schleswig-Holstein where *UUS* is explicitly included in the planning area (Bartel and Janssen, 2016). Bartel and Janssen (2016) object to the notion of a strict depth-wise division of spatial plans and suggest *subsurface planning* by geological characteristics instead, in analogy to planning of water resources for catchment areas.

In the Netherlands, the *National Spatial Plan for the Underground* is under discussion at the time of writing (Admiraal and Cornaro, 2016a). A depth-wise division of jurisdictions of different authorities is also under discussion (Admiraal and Cornaro, 2016a). Being subject to national and international legislation, archaeology and soil pollution are the subsurface issues traditionally considered in spatial planning processes in the Netherlands (Dick et al., 2019). However, other themes, such as groundwater, geothermal energy and physical space underground, are often taken into account in the plan realisation phase at project scale (Dick et al., 2019).

In many other countries, *subsurface planning* is usually limited to different sectors which produce discrete sectoral plans for separate subsurface uses, e.g. mining, mass transport, infrastructures for the management of energy and water supplies, sewage treatment plants, safety analysis and telecommunication networks. Sector plans such as this were developed for Montreal, Toronto (CA), Brisbane (AU), Istanbul (TR) (Delmastro et al., 2016), Tokyo, Osaka and Nagoya (JP) (Kishii, 2016). Examples of sectoral planning for tunnels can be found in Sweden (Tengborg and Sturk, 2016), Norway (Broch, 2016) and Slovenia (Uršej and Kontić, 2007). Von der Tann et al. (2018) point out that current governance of the *subsurface* in England is likewise largely sectoral, and the *subsurface* is managed locally on a project-by-project basis.

Table 4

An overview of decision support frameworks and methods for inclusion of the subsurface into spatial planning processes as a multifunctional resource. Map: visualisation of the subsurface potential.

Subsurface aspects	Scale	Origin	Case study	Map	Reference
The Deep City Framework					
Underground resources: physical space, groundwater, geothermal energy, geomaterials.	City	CH	The cities of Geneva (CH), Suzhou (CN), Shanghai (CN), and San Antonio (USA)	Yes	Parriaux et al., 2007; Li et al., 2013a, b; Li et al., 2016a,b, 2018; Doyle, 2016; Doyle et al., 2016
Urban Underground Resources Exploitation					
Underground resources: physical space, groundwater, geothermal energy, geomaterials.	City	CH	Hypothetical case	No	Blunier et al., 2007
Urban Futures* (UF) *Related Frameworks					
Subsurface uses: physical space, water, energy and related emissions, and waste.	Project	UK	No	No	Hunt et al., 2011
Subsurface functions as geoassets.					Hunt et al., 2016
Local conditions: physical environment, socio-economic aspects, location aspects, biophysical environment.			Birmingham Eastside (UK)	Yes	Makana et al., 2016
Subsurface functions: bearing capacity to support development (platform), groundwater flow (provisioning), geothermal gradient (provisioning), preservation of buried cultural deposits (cultural) and access to urban green space (cultural).			No	No	Price et al., 2016
UUS indicators: foundation conditions, ground source heat potential, and infiltration potential.			Earl Court in London (UK)	Yes	Price et al., 2018
Geoassets: geology, asset interaction, topography, environment, hydrogeology and history.			No	No	Shah et al., 2014
***Asset Management of the Subsurface* (AMS)**					
Subsurface functions as man-made and natural assets.	Project	NL	No	No	Maring and Blauw, 2018
***System Exploration Environment and Subsurface* (SEES)**					
Subsurface qualities; see Fig. 6.	Project	NL	Merwevierhavens in Rotterdam (NL)	Yes	Hooijmejer & Maring, 2013, 2018
The Balance 4 P Framework					
The Dutch SEES is applied as a step in the framework; subsurface qualities; see Fig. 6. The framework is focused on the decision-making process itself (who, when, how).	Project	SE	Merwevierhavens in Rotterdam (NL), Alvat in Buggenhout (BE), Fixfabriken in Gothenburg (SE)	Yes	Norrman et al., 2015a,b; Norrman et al., 2016
Framework Services of the Earth					
Geosystem services; see Fig. 5	Project	NL	No	No	Van Ree et al., 2017

7. Decision support for sustainable use of the subsurface

7.1. General recommendations in the literature on sustainable subsurface use

According to Admiraal and Cornaro (2016b), for the use of *UUS* to be sustainable it should fulfil four criteria: (1) the development is sustainable itself, (2) any excavated material must be sustainably reused, (3) it should not hinder future uses of the *subsurface* and (4) the development must allow for reuse of the developed physical space. Further to this, Qiao and Peng (2016) point to three main aspects to ensure effective use of *UUS*: (1) recognition of *UUS* by decision-makers, (2) regulatory planning of *UUS* and (3) proper management to realise *subsurface planning*. Griffioen et al. (2014) state that the use of the subsurface should contribute to the well-being of humans and to the prosperity of society without irrevocable damage to other interests of present and future generations, while sustainability assessments should include three elements: 1) relating to the subsurface use itself (efficiency, duration, optimisation and scarcity); 2) associated with the public interest (political goals, usefulness and need, effect and consequence); and 3) stemming from legal principles of environmental policy (precautionary principle, obligation of care). Further, Griffioen et al. (2014) argue that a) management should be driven by scarcity, b) closed loop monitoring should be implemented when subsurface activities are high-risk, c) responsibility and liability for damage must be set out in regulations, and d) sustainability should be incorporated in all relevant legislation (not only in environmental legislation).

Bobylev (2009) identifies the actions needed for mainstreaming *UUS* and sustainability issues into master plans, and provides the following recommendations: (1) to implement 3D planning, (2) to prioritise *UUS* services, (3) to study prospective functional and spatial interrelations between different types of infrastructures, and (4) to perform integrated assessments to support decision-making. Hunt et al. (2016), referring to Bobylev (2009), specify four aspects which must be considered for larger (and more sustainable) use of *UUS*: (i) existing conditions, (ii) opportunities for new constructions, (iii) rehabilitation or reuse, planning policies, governance and legal frameworks, and (iv) recognition and acceptance of *UUS* in spatial planning processes. To encourage and monitor progress towards sustainable development and make *UUS* issues visible to policy makers, Bobylev (2016a),b recommends creating an inventory of *UUS* assets while also accounting for useful metrics: (1) developed *UUS* volume (m^3), (2) *UUS* use density (m^3/m^2), and (3) developed *UUS* volume per person (m^3/person). Moreover, Bobylev (2016a,b), stresses that geosystem and ecosystem services may provide an improved basis for *subsurface planning*, assigning a value to the *subsurface* and thus ensuring its rational use.

Kaliampakos and Benardos (2008), and Kaliampakos et al. (2016) also highlight the importance of assigning a value to the *subsurface*, in order to prevent its overexploitation and suboptimal use. The authors of these particular papers argue that ignorance of the value of physical space underground can lead to incorrect or misleading assumptions about the *subsurface* in spatial planning processes, and as a result opportunities can be lost in terms of various benefits that the *subsurface* might otherwise offer. According to Kaliampakos and Benardos (2008), ignorance of the value of the subsurface stems from the lack of theoretical valuation methods which can be applied to *underground space*, in contrast to well-established and standardised methods for valuation of land units and fixtures aboveground. Kaliampakos et al. (2016) argue that together with internal project costs and benefits, the external social effects of the physical space use should be incorporated into the economic assessment of underground projects.

7.2. Decision support for subsurface planning

Without being exhaustive, an overview of the developed frameworks and methods for inclusion of the subsurface in spatial planning processes is presented in Table 4.

8. Discussion

8.1. A common language

Several authors stress that communication and knowledge exchange between the different disciplines involved in spatial planning processes is a necessity for capacity building and thus more sustainable use of the *subsurface* (e.g. Zargarian et al., 2013; Admiraal and Cornaro, 2016b; Norrman et al., 2016; Besner, 2016; Campbell et al., 2017; Hooimeijer and Maring, 2018). Campbell et al. (2017) emphasise the importance of creating "improved urban subsurface knowledge which must … be effectively communicated, delivered and accessible to, and useable by urban planners and other decision- and policymakers, and practitioners". The existing communication and knowledge gaps must be bridged by appropriate subsurface information, easily conveyable in the right format and at the right time (Campbell et al., 2017), in the right quantity (Mielby et al., 2017b) and of the requisite quality (Norrman et al., 2016). Hence, to make this deliberate act of cooperation effective, there is a need for a common language as a fundamental precondition of knowledge exchange. Currently, different authors use different terms but mean the same thing, e.g. *underground*, *subsurface*, *ground*. On the other hand, others use same terms but mean different things, e.g. *underground space* as physical space created or used underground, and *urban underground space* that encompasses *underground*, *subsurface*, *ground* in urban areas and provides multiple *underground resources*, e.g. physical space, water, energy and materials. Furthermore, some see geosystem services as abiotic *ecosystem services* (Gray, 2012; Gray et al., 2013), while others emphasise that *geosystem services* are both biotic and abiotic (van Ree et al., 2017).

8.2. Subsurface as a resource – stocks of assets vs flows from stocks

A common understanding of the *subsurface* as a multifunctional resource is a fundamental precondition for knowledge exchange between different disciplines in a *subsurface planning* process. Extensive *UUS* use, in terms of physical space, is argued to be an indirect indicator of cities' maturity and wealth Bobylev (2016a,b). However, in many countries worldwide, the "first-come-first-served" or, in legal terms, the "first-in-time-first-in-right" principle still applies to getting access to the resources in the *subsurface* (e.g. Sprankling, 2008; Bobylev, 2009; Admiraal and Cornaro, 2016a; Bartel and Janssen, 2016; Tengborg and Sturk, 2016; Pfleiderer et al., 2016). This naturally risks their irresponsible and suboptimal utilisation and overexploitation. In order to take strategic decisions on the most sustainable and efficient use of the *subsurface*, it must be recognised by decision- and policymakers as a precious, multifunctional and finite resource, one that should be managed in accordance with its full potential (e.g. Griffioen et al., 2014; Admiraal and Cornaro, 2016a; van Ree et al., 2017) and its value to society (e.g. Price et al., 2016; Bobylev, 2016a,b; van Ree and van Beukering, 2016; Maring and Blauw, 2018). In this regard, the precautionary principle should be applied to the *subsurface* because decisions on granting priority to a specific *subsurface function*, e.g. space for infrastructure, to serve one specific need at a given time can irrevocably damage not only the environment, but also the present and future generations' opportunities to utilise other *subsurface functions* in a given space. Furthermore, secondary utilisation of the natural or constructed underground space – i.e. for purposes other than originally designated – should be considered to address new needs that emerge in the surrounding area or as a mean to correct a previously wrong decision on the type of utilisation. Secondary utilisation of previously developed underground space is crucial for efficient reuse of underground space. Only in Sweden, there are numerous examples of such reuse: Aeroseum – an aviation museum in a former underground aircraft hangars, Dalhalla – a former limestone quarry converted into a magnificent outdoor music venue, Knalla Mine – an abandoned mine comes to life and boosts tourism industry, Kvarntorp logistics and test facility – new uses for a former limestone mine, Pionen – a nuclear bunker transformed into a futuristic data centre, the Skeppsholmen Caverns – exhibition halls in a former military facility (Lindblom et al., 2018). Yet another example of reuse is the former bomb shelter in London from World War II now turned into an underground farm (Growing Underground, 2019). When planning for new developments of underground spaces the design should preferably take future reuse in consideration.

A unifying feature of the reviewed scientific studies is recognition of multiple *underground resources* – physical space, water, energy and geomaterials (e.g. Parriaux et al., 2004, 2007; Doyle et al., 2016; Admiraal and Cornaro, 2016a). Such subdivision is especially common in the field of engineering. Some studies also add the components of life-support systems, habitats for ecosystems and the notion of an archive of archaeological and geological heritage (e.g. Admiraal, 2006; Bobylev, 2009; de Mulder et al., 2012; Gray, 2012, 2013; van Ree et al., 2017; Tummers and Hooimeijer, 2016). However, different authors and research groups highlight different aspects of the *subsurface* as a resource. In the field of engineering the focus mainly rests on the *subsurface* as a stock of natural (e.g. caverns, fossil fuel, water) and human-made (e.g. tunnels, utilities) assets used for construction, storage and extraction purposes (e.g. Parriaux et al., 2004, 2007; Doyle et al., 2016; Admiraal and Cornaro, 2016a). A more holistic view holds that the *subsurface* provides multiple (sometimes competing) *eco-* and *geosystem services* (see Gray, 2012; Gray et al., 2013; van Ree et al., 2017), which are beneficial biotic and abiotic *flows* arising from the stocks of natural assets underground and fulfilling human needs (van der Meulen et al., 2016a; van Ree et al., 2017). This holistic view implies shifting focus from man-made objects underground to *subsurface functions* which form natural and man-made assets and, in this way, create potential or actual values by providing services to humans (Maring and Blauw, 2018). Such a holistic view on the *subsurface* is held by a great many researchers across different research contexts and disciplines (see e.g. Admiraal, 2006; Bobylev, 2009; Hooimeijer and Maring, 2013, 2018; Griffioen et al., 2014; Price et al., 2016; van Ree et al., 2017; Maring and Blauw, 2018).

8.3. Subsurface in policy and regulation

Our review of information on subsurface legislation available in the academic literature reveals two different legal aspects of subsurface use: the first is concerned with property rights to the *subsurface* (e.g. Japan and Singapore), whereas the second deals with regulations on *subsurface planning and development* giving the responsible institutions rights to reserve certain areas for underground constructions (e.g. Finland). Regulations on property rights to *subsurface* by depth (Japan and Singapore) is assumed to facilitate use of the deep *underground* for construction without the need to possess property rights to corresponding property units aboveground (Zhou and Zhao, 2016; Kiishi, 2016). In response to new underground space technologies and global climate change, several studies stress that, as for the upper stratum, the stratum below a depth limit of reasonable use by the land owner should be regarded as part of the public domain (e.g. Sprankling, 2008; Morgan, 2013; Dick et al., 2019), which is owned by no one and available for use by everyone, i.e. *res nullius* and *res omnium communis* (Morgan, 2013), respectively, as opposed to *cuius est solum*. In contrast, van Ree et al. (2015) suggest that the subsurface lease model would fairly distribute the benefits of subsurface use among the land owners of corresponding property units. The legislation related to property rights is expected to assist in exploitation (utilisation) of the *subsurface* for development needs, referred to by Admiraal (2006) as the top-down approach to *subsurface planning*. In the reviewed literature sources, however, less attention is paid to the preservation of *underground resources* and their sustainable use – a bottom-up approach to *subsurface planning* in accordance with Admiraal (2006) – which is usually stipulated by environmental laws. In this respect the Netherlands is a pioneering country which is working on balancing these two approaches by merging environmental, planning and building acts into one legal instrument while at the same time strengthening the role of the *subsurface* in spatial planning (Lamé and Maring, 2014).

It should be noted that information on regulations and policy for subsurface use is limited and fragmented, although interest in and use of *UUS* have significantly increased recently, as summarised in Bobylev and Sterling (2016). Moreover, although research on how best to integrate the *subsurface* with the *space* above in spatial planning processes has been going on for more than 40 years, *subsurface planning* is still ill-regulated worldwide (Table 3). No clarification on why this is the case was found in the reviewed literature sources, although Dick et al. (2019) point out that sorting out subsurface aspects which must be strictly regulated in legislation from those which could be included in policy is an inherently difficult challenge. Furthermore, interpretation of planning and environmental laws by institutions engaged in spatial planning might be linked to acknowledging natural resources in the *space* above the surface in two dimensions – height and width – while access to resources in the *subsurface* also implies a third dimension of depth. The third dimension, with the exception of depth limits for the regulation of property rights, does not seem to be specified in law and is ignored in its interpretations.

8.4. Subsurface planning and decision support

As stated in the landmark Stockholm Declaration of the United Nations Conference on the Human Environment from 1972, "[t]he natural resources of the earth … must be safeguarded for the benefit of present and future generations through careful planning" (UN, 1972). Hence, careful *subsurface planning* is required for preventing uncontrolled subsurface utilisation – which sometimes results in misuse and irrational consumption of *underground resources* (Kaliampakos and Benardos, 2008) as well as overexploitation and community-wide hazards (Admiraal and Cornaro, 2016a) – to achieve fair inter- and intragenerational distribution of limited natural resources. Being stipulated by legislative frameworks and planning traditions, the development perspective on *subsurface planning* can often be observed in the literature (e.g. Broch, 2016; Delmastro et al., 2016; Kishii, 2016; Qiao and Peng, 2016; Tengborg and Sturk, 2016; Vähäaho, 2016; Zhou and Zhao, 2016; Zhao et al., 2016; Zhang et al., 2017), i.e. planning of the physical space. For example, underground master plans are expected to contain existing and future facilities and tunnels, space reservations for developments, access links to technical maintenance facilities and tunnels, new locations for various functions, engineering requirements and guidelines (Delmastro et al., 2016). This type of plan is clearly linked to construction and management of existing and future infrastructures underground at city scale – would it not still lead to a sectoral approach of disintegrated consideration of multiple *underground resources* one by one to serve one specific need at a given time? Singapore and the Netherlands are working on just such plans at city scale whereas Finland has already developed a legally binding underground master plan for Helsinki. The aboveground development in Helsinki must therefore comply with the geological conditions and space reservations for future constructions underground. For urban planners and urban designers, the challenge in planning lies "in appreciating that the geology strongly determines what is possible" to construct above and below ground (Admiraal and Cornaro, 2016a).

Nevertheless, driven by the attempt to overcome another challenge of making multiple *underground resources* visible and acknowledged in spatial planning processes, the resource perspective on *subsurface planning* is held by a vast majority of researchers (e.g. Parriaux et al., 2004; de Mulder and Pereira, 2009; Bobylev, 2009; Hooimeijer and Maring, 2013, 2018; Griffioen et al., 2014; Makana et al., 2016; Norrman et al., 2016; van Ree et al., 2017; Maring and Blauw, 2018). This perspective is linked to a holistic view on the *subsurface* as a multifunctional resource which provides *eco-* and *geosystem services* and forms both man-made and natural assets. Many of the decision-making frameworks and methods that were reviewed (see Table 4) include *subsurface mapping*, i.e. visualisation of the *subsurface* as a multifunctional resource with the help of subsurface potential maps at city scale (Li et al., 2013a; Li et al., 2016b; Doyle et al., 2016; Li et al., 2018) and at project scale (Hooijmejer and Maring, 2013, 2018; Makana et al., 2016; Norrman et al., 2015a). Unfortunately, the opportunities presented by the *subsurface* at project scale can be lost or constrained by the existing sectoral plans at larger scale. Therefore Parriaux et al. (2007) emphasise the criticality of resource-based *subsurface planning* at city scale to avoid sectoral planning and subsequent suboptimal solutions for subsurface use, providing an extreme example of a subway constructed in a valuable aquifer. Von der Tann et al. (2019) stress that sectoral approaches to spatial planning should be substituted with a systems approach or ecosystem-based approaches. The focus of the former rests on the involvement of stakeholders and the process itself (von der Tann et al., 2019). Furthermore, to make multiple *underground resources* acknowledged in the decision-making process, several authors focus on the *subsurface* as an asset (Price et al., 2016; Shah et al., 2014; Maring and Blauw, 2018). Although confidential information (such as sensitive commercial and security data) on man-made objects underground may also present a challenge in spatial planning processes, studies which address this topic were not found.

9. Conclusions

Analysis of the findings from this literature study suggests:

- The *subsurface* must be recognised not only by scientists but also by decision- and policy-makers and other stakeholders as a precious and multifunctional resource, which provides physical space, water, energy, materials, habitats for ecosystems, support to surface life and holds cultural heritage and geological archives. Careful planning and sensitive management of the *subsurface* needs to be stipulated.
- One *underground resource* (e.g. physical space) can provide several competing or coexisting *subsurface functions* – e.g. space for infrastructure and space for storage of gas, oil, carbon dioxide and waste – which turn into services when utilised by humans.
- The *subsurface* comprises both man-made and natural assets and in this way creates actual or potential values to humans. Ignorance of these values can lead to incorrect or misleading assumptions about the *subsurface* in spatial planning processes, and as a result opportunities can be lost in terms of various benefits that its responsible use might otherwise offer.
- Utilisation of the different *subsurface functions* to yield services requires not only careful planning but also a framework to support the decision-making process in achieving a balance between utilisation and preservation; where a decision is made to utilise fully rather than preserve the various *subsurface functions* a balance between the different usages should also be sought.
- To facilitate the change towards transdisciplinary work settings in the spatial planning processes and form a platform for knowledge exchange and capacity building, there is an urgent need for *a common language*, i.e. mutually understandable terminology, and *a common understanding*, i.e. an all-inclusive view on the *subsurface* as a complex multifunctional resource. Although not yet fully developed, *geosystem services* can be a key concept to achieve this.
- To overcome the "first-come-first-served" problem and thus enable fair inter- and intragenerational distribution of limited natural resources as well as sustainable development of cities, it is necessary to:
- Shift the focus from man-made objects underground to *subsurface functions*;
- Create the right conditions – mainly facilitated by making available timely, accessible and high-quality subsurface information – for bridging the communication gap between engineering geologists, civil engineers, architects, urban planners, urban designers and other stakeholders in spatial planning processes;
- Investigate and map multiple subsurface potentials on a city scale to prevent lost opportunities at both city and project scales, including the potential to reuse already exploited space;
- Balance development and resource perspectives on *subsurface planning* for prioritisation and optimisation of competing subsurface

uses, and resolution of potential conflicts of interests;

- Ensure through legislation that the precautionary principle is applied when allocating *underground resources*;
- Bring into focus the decision-making process itself (who, when, how) to support sustainable solutions on subsurface use, rather than the decision-support tools and methods themselves.

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Appendix A

See Table A1.

Table A1
Overview of search strings used in SCOPUS for the literature review and corresponding hits. Excluded studies in the final step relate e.g. to geology and geoscience in planning in general, focus only on a development perspective (underground construction and physical space), subsurface data and 3D data, older studies by authors where new publications with same authors are already included, book chapters and papers in languages other than English. TUST = the journal of Tunnelling and Underground Space Technology.

Date (most recent)	Search string	Hits	Possible relevance	Included
19-04-16	*subsurface* AND *planning*	2,262		
19-04-16	… within results: *classification*	194	6	5
19-04-16	… within results: *terminology*	14	0	0
19-04-24	…limit to TUST	26	11	11
19-04-16	"*subsurface management*"	35	9	4
19-04-16	"*subsurface planning"*	20	12	7
19-04-26	"*subsurface use*" AND *planning*	22	5	4
19-04-16	*underground* AND *space* AND *planning*	878		
19-04-16	… exclude TUST	801	55[a]	13
19-04-16	… exclude TUST, limit 2017-2019	110	16	2
19-04-26	… limit to TUST	117	35	32
19-04-16	"*underground space*"	1,976		
19-04-16	… exclude TUST, within results: *classification*	118	22	4
19-04-16	… exclude TUST, within results: *terminology*	6	2	0
19-04-29	… limit to TUST	221	37	33
19-04-16	"*underground space planning*"	48	18	5
19-04-12	*subsurface* OR "*underground space*" OR *underground*	219,945		
19-04-12	…AND "*confidential information*"	2	0	0
19-04-12	…AND "*confidential information*" AND *planning*	1	0	0
19-04-12	…AND "*classified information*"	3	0	0
19-04-12	…AND "*classified information*" and *planning*	0	0	0
19-04-12	…AND *secrecy*	24	0	0
19-04-12	…AND *secrecy* AND *planning*	0	0	0
19-04-12	…AND "*confidentiality*"	14	0	0
19-04-12	…AND "*confidentiality*" AND *planning*	1	0	0
19-04-12	…AND *valuation* OR "*economic assessment*"	500	3	3
19-06-02	*Subsurface*	104,338		
19-06-02	… AND *"property rights"*	23	4	2
19-06-02	… AND *"3D cadastre"*	4	1	0
19-06-02	… AND *"planning law"*	0		
19-06-02	… AND *"planning regulation"*	0		
19-06-02	… AND *ownership*	70	11	7
19-06-02	*"underground space"*	2,077		
19-06-02	… AND *"property rights"*	8	6	2
19-06-02	… AND *"planning law"*	0		
19-06-02	… AND *"planning regulation"*	1	1	1
19-06-02	… AND *ownership*	23	18	6
Sum (note that there are several overlaps in hits between searches)				*141*
Total number of references in manuscript (note that some are not from the searches)				*121*

[a] Too many hits to go through, sorted by number of citations, 55 studies of possible relevance relate to sorting within studies with at least two citations.

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