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Urban Futures: the sustainable management of the ground beneath cities

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Abstract: Over half of the world’s population now live in cities. In 2011 it was estimated that the global population exceeded 7 billion. Pressures on the environment including land-use are increasing. The ground beneath cities and the interaction between physical, biological and chemical processes, provides natural capital on which society depends. These benefits and the ground properties and processes that support and deliver them, can be considered ecosystem services.

Characterising the ground properties on which ecosystem services depend, involves a qualitative assessment of positive and negative impacts of proposed urban sustainability solutions, including use of the ground. The sustainability of a proposed solution depends on how the future might unfold. Future scenario analysis allows consideration of the social, technological, economic, environmental and political changes that may determine the ability of a proposed solution to deliver its benefits now and in the future. Analysis of the positive and negative impacts of a proposed use of the ground on ecosystem function, measured against future scenarios of change, can be integrated to deliver strategies for the future management of the ground and the wider environment beneath cities. *[end of abstract]*

Cities, their function and sustainability

Over half of the world's estimated 7 billion people now live in cities. By 2050 the global population is estimated to increase to 9.3 billion with 6.3 billion people expected to be living in towns and cities (United Nations Department of Economic and Social Affairs Population Division, 2012a). This projected increase would result in 68% of the world's population becoming urbanised by 2050. The percentage of the current world's urban population living in cities is not evenly spread however. Whilst 50% or more of the population of global regions including Europe and North America are urbanised, regions such as Asia and Africa are not expected to reach that level until 2020 at the earliest (Fig. 1). Regions within the United Nations definition of 'least developed' are expected to see the greatest proportion of urban growth to 2050. Asia's urban population is expected to increase by 1.4 billion, Africa 0.9 billion and Latin America and the Caribbean by 0.2 billion.

Urbanisation has resulted in the sequential use of the ground through time. The ground is taken to include the surface of the land and its geological subsurface. The ground provides the foundation to support development on it and within it. Its properties govern the physical and biogeochemical processes that operate within including the flow of water, heat and attenuation of contaminants. The repeated use of the ground by disparate organisations for different uses has resulted in above and below ground urban development that is often poorly coordinated. The demands placed on the ground, including its physical resource as a medium for tunnelling, exchange of heat and the fluids it contains are in competition and may result in conflict for their use.

It is essential to characterise the function of cities and the benefits that society gains by using the ground beneath them. The benefits that society derives from the use of underground space can be considered as natural capital. Natural Capital is the sum of all the assets derived from the earth's environment, which are essential for people to live. It can include assets derived from soil, water and living things that provide benefits including food and shelter. Recognition of the role that the environment plays in delivering the essential functions for day-to-day human well-being can be considered ecosystem services.

Although often associated with ecology and biodiversity, land and its geological subsurface should be explicit in the definition of natural capital. The degree to which subsurface natural capital provides those benefits is dependent on the condition of the ground defined by its geological, geotechnical, hydrogeological and geothermal properties.

People and cities

Many considerations of the impact of global urbanisation focus on the total population within a city as a proxy for its impact on the environment. It may be measured by other proxies including resource use, energy demand, waste production, carbon dioxide emissions or construction. Marker (2009) highlighted the development of global megacities and their potential impact. In 2011, there were 23 megacities with populations of 10 million or more accounting for 9.9% of the world's urban population (United Nations Department of Economic and Social Affairs Population Division, 2012b). In 1970, only Tokyo and New York were classified as megacities. In 2011, Asia was home to 13 megacities, Latin America 4 while Africa had 2. It is predicted that much of the growth in megacity development to 2025 will take place in Asia with the addition of a further 9, giving rise to 37 megacities worldwide, accounting for an estimated 13.6% of the world's urban population (United Nations Department of Economic and Social Affairs Population Division, 2012a). The population growth within megacities between 1970 and 2025 is illustrated in Table 1.

The development of megacities and the net change in the number of their inhabitants raises an important characteristic of historical and future urban growth. The distribution of the world's urban population is unevenly distributed amongst cities of different size (Fig. 2). In 2011, cities with fewer than 1 million people accounted for approximately 60% of the world's urban population. Of that, almost half of the people lived in cities with a population less than 500 000. By 2025, approximately half of the world's urban population will live in cities of 1 million or more inhabitants and by 2050 it is estimated that there will be 360 cities with populations of 1 million or more (Marker, 2009).

This has important implications for the current and future management of the environment and its natural capital in cities. Cities whose populations are large may also be dense and focused within well-defined municipal regions. There may be greater opportunity for coordinated and integrated land-use planning, waste disposal and resource use at the local scale, delivering maximum benefit to a large number of people. In contrast, cities with fewer people separated geographically and politically may result in less effective and disparate city planning. The implication is that if the projection towards increasingly dense urban areas continues, it may provide the best opportunities for future sustainable city management. The potential opportunities for urbanisation to reduce environmental impact and resource consumption through efficiency measures is recognised by Royal Society in the United Kingdom as part of its assessment of the relationship between the people and the planet (The Royal Society, 2012).

Rates of urban development

The rate of development of cities is another important factor in defining the impacts of urbanisation and its sustainable management. The United Nations Department of Economic and Social Affairs Population Division (2012a) recognise that rates of annual city growth have declined in developed countries that experienced rapid growth in response to large scale industrial development and economic growth in the 18th and 19th centuries. Deindustrialisation and suburbanisation are interpreted to be two contributory factors in some cities shrinking in Western Europe and the USA (Martinez-Fernandez et al., 2012). In contrast, urban growth rates of 2% or more are predicted in cities including Lagos, Nigeria, Dhaka, Bangladesh and Karachi, Pakistan. Cities including Abu Dhabi and Dubai in the United Arab Emirates are examples of cities that have experienced rapid growth in direct response to large-scale economic and political ambition. In other countries including China, the likely creation of cities and migration of people from rural to urban areas is driven by strong political ambition for cities to be centres of economic growth. Environmental change including increased instances of flooding and desertification drives people to and from cities.

The rate at which populations change is a function of variations in the combined influence of social, economic, political and technological drivers. Many cities reflect this variability as repeated cycles of land-use turnover and exploitation of the ground. Towns and cities commonly develop an historical core subject to successive phases of development. Such phases often preserve anthropogenic land-use legacy either as cultural heritage deposits and landforms (Carver, 1987; Holden et al., 2006) or as a legacy of environmental degradation including contaminated land and subsidence. Cities may expand laterally away from their historical cores often forming a fringe of industrial, retail and large-scale residential development around it and often consuming previous suburban developments. This form of suburbinisation may then result in city decline and shrinkage (Martinez-Fernandez et al., 2012). This style of urban development often gives rise to large and mature cities whose growth may have taken place, a least in its initial phase, without strategic planning (Marker, 2009). Other cities, including Abu Dhabi and Dubai are examples of young cities that have developed rapidly over tens of years in response to accelerated economic and social development. These cities, in common with post-war ‘new towns’ in the United Kingdom, grew in areas where there was limited previous development and land was not subjected to successive phases of land turnover.

City functions, ecosystem services, natural capital and urban metabolism

Cities are required to provide a range of services that allow them to function so that people can live, work and move around within, above and below them. The city environment enables people to do this through functions including the provision of space for development (buildings, utilities, and tunnels), regulation and exchange of heat, provision of water, disposal of wastes, recreation and biodiversity. Cities can therefore be viewed as providing essential services or natural capital that benefits the people within them (Bobylev, 2009). Many of these essential benefits and functions are buried in the ground and out of sight. The ultimate result of global urbanisation is that competition for space and development is likely to increase. A city must deliver its core services regardless of it being young or old and regardless of its history or use or the availability of its natural capital resources required to deliver it.

The Millennium Ecosystem Assessment (Corvalan et al., 2005) and related national ecosystem assessments such as the United Kingdom National Ecosystem Assessment (UK National Ecosystem Assessment, 2011) recognise the key functions of the environment that relate to societal well-being, health and operation. The main ecosystem services operating within the urban environment and the goods derived from them, are shown in Table 2. The environment in this context is taken to include the combined products of natural and anthropogenic systems and processes. Rawlins et al., (2014) in considering the climate change impacts on urban soil function, proposed an additional ecosystem function called ‘platform’ in recognition of the properties of the ground that provide support for development including bearing capacity and electrical earthing potential.

The concept of ecosystem services and the goods they provide is increasingly recognised in planning and environmental policy. The United Kingdom’s environment white paper (Department for Environment Food and Rural Affairs, 2011) recognises the role that the environment plays in delivering the goods and services (recognised as natural capital) on which society depends for its well-being and as a means of achieving economic growth as well as protecting the environment. Importantly it recognises that services to support and deliver the core functions of cities may come from within or beyond the city boundaries. The UK National Ecosystem Assessment (Davies et al., 2011; UK National Ecosystem Assessment, 2011) also provides a qualitative assessment of trends in the type of ecosystem system by determining relative net changes (positive or negative) in the quality of provision since 1990. This type of natural capital assessment therefore provides a means of measuring the functions of cities, the quality of its provision and vulnerability or resilience to future change.

Many ecosystem services provided by the ground and its constituent properties are delivered by soils, derived from their natural and anthropogenic parent materials. Soils as a non-renewable resource and their constituents of mineral and organic matter, water and air, provide core services on which the health of the urban environment depends (Blum et al., 2006). These services include support for plant growth and nutrition, regulation through filtration and attenuation of water, inorganic and organic compounds and provision of ecological biodiversity, food and fibre. The ability of soils to maintain these functions is often threatened in urban areas as a result of anthropogenic activity including ground excavation and surface sealing (Burghardt, 2006) . Processes resulting in soil compaction or surface sealing reduce one or more soil functions that affect their ability to deliver their services. Compaction and sealing leading to increases in surface water run-off through reduced infiltration capacity is one example of loss of an ecosystem service.

How well these properties perform and deliver their benefits could be considered in the context of cities as an organism. This is recognised through the concept of urban metabolism and can be defined as ‘the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy and elimination of waste’ (Kennedy et al., 2007). Kennedy et al., (2011) recognise that in practice urban metabolism includes the quantitative assessment of the combined inputs, outputs, storage and consumption of energy, water, nutrients, materials and wastes within an urban area. Kennedy et al., (2011) notes that the quantitative application of urban metabolism can be used to define key functions of the city environment and their performance (a measure of how well they are performing) as a measure of the current or future sustainability of cities in their design and function.

Sustainable urban environments

The most commonly considered definition of sustainable development is ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (Brundtland, 1987). Delivering sustainability requires an understanding of those needs on the basis and interaction of the three pillars of sustainability: environment, economy and society. Complexity exists within the interactions between these three pillars. For example, development and economic growth may take place at the expense of environmental performance or quality. Rogers (2009) notes that the Bruntland definition could be taken to mean ‘maintain the status quo’ as it does not provide an implicit aspiration to improve or enhance the measures of societal, economic or environmental performance.

The future sustainable development of cities will be dependent on the successful function and continued performance of the natural capital provided by the cities environment, including its subsurface. The use of the urban environment, including interventions through construction and civil engineering, will require the qualitative or quantitative assessment of the ecosystem services affected by it so that the delivery of its goods (natural capital) will not be adversely affected. This is considered in current construction practice, although it may not be recognised as such (Rogers, 2009). In addition, the assessment of the environmental or geotechnical impacts of the intervention may not currently be recognised as an assessment of the impact on ecosystem services.

Geohazards, geoassets and the use of underground space

Underground space

Many countries have already realised social, economic and environmental benefits by using the ground beneath cities for a variety of purposes. Rogers (2009), Jefferson et al., (2009) and Paul et al., (2002) report that countries including Hong Kong, Singapore, the Netherlands, Canada and Denmark, have adopted underground space for uses including hydrocarbon storage, wastewater treatment, car parking and retail. The drivers for using underground space include limited above ground space, geomorphological controls (e.g. coastal cities, steep slopes), environmental protection and favourable ground conditions. Common uses of the subsurface in other cities worldwide include underground transportation, basements and foundations and burial of utilities. De Mulder et al., (2012) identified 7 classes of subsurface function that can be considered in the context of the ecosystem function and natural capital and include:

- source of natural resources
- storage of materials (solid, liquid, gas)
- space for public and commercial use space for infrastructure
- medium for foundation for construction
- component in life-support systems
- archive of historical and geological heritage

The concept of people spending time in subterranean spaces is familiar but more readily recognised in relation to underground transportation, retail and car parking. The citizens of many cities of the world already spend much time underground in direct response to their local climate. Residents of towns and cities including Montréal and Toronto, Canada, Coober Pedy, Australia and Beijing, China all spend significant time underground to escape hot summers or cold winters (de Mulder and Pereira, 2009; de Mulder et al., 2012). There is increasing global recognition of the opportunities for subterranean development although their social acceptance as genuine solutions for living remains some way off. Designs for 'geodomes' comprising connected underground structures between 50 and 500 m below ground level and maintaining constant and predictable temperatures provide options for storage and even recreation (de Mulder et al., 2012).

Early subsurface exploitation for human benefit focused on its provision of basic needs for human survival; shelter, water and mineral resources (tools and energy). Later uses included those associated with drainage, mining and transport infrastructure, involving increasing depths of underground space use. Burial of municipal and nuclear waste, sequestration of carbon dioxide (utilising pore space in compatible rock) and construction of caverns for the storage of hydrocarbons, wastewater treatment works, military shelters and operations bases and transport became common in the 20th Century. The very shallow subsurface (less than 3 m) has become a heavily used and increasingly congested space in cities through the installation and burial of utilities including those for water, gas, telecommunications and electricity. Fig. 3 schematically illustrates the progressive use of underground space beneath cities through time.

The exploitation of underground space through tunnel construction, piled foundations, excavation of trenches or cut-and-cover excavation has resulted in a complex network of subterranean structures and objects. Even in young, developing cities like Abu Dhabi and Dubai in the United Arab Emirates, the presence of deep piled foundations supporting high-rise residential, retail and office developments and the utility and drainage networks to serve them, have resulted in widespread subsurface space use to 80 m below ground level. This level corresponds to the approximate depth of the construction of buried sewerage networks as part of the Strategic Tunnel Enhancement Project and its associated wastewater pumping stations (http://www.adssc.ae/en-us/Steps/Pages/Snappy.aspx).

Evans et al., (2009) and de Mulder et al., (2012) recognise the likely future increase in the use of subsurface space. Evans et al., (2009) consider expansion of current and development of future uses of the subsurface including those outside the municipal boundaries of cities. Those uses may include underground gas storage (in the pore space of suitable sedimentary rocks or in caverns), compressed air storage (CAES), carbon dioxide capture and storage and disposal of solid wastes. Future city uses may include mass occupancy spaces for retail, leisure and transport, data storage and retrieval, infiltration of surface water through sustainable drainage systems (SuDS), increased groundwater abstraction and heating and cooling of buildings using geothermal energy.

The choice and efficiency if future uses of the subsurface will depend on the inherent properties of the ground to deliver the function for which it was designed. To meet sustainability objectives, each service should be designed to function whilst minimising negative impacts on or enhancing the surrounding environment, providing economic development and supporting societal well-being. To deliver these objectives, any intervention in the subsurface must also take account of the legacy of previous underground development.

Sustainable approaches to future subsurface use must therefore consider three main elements:

1. Evaluation of the suitability of the ground to meet the design and performance criteria of the proposed subsurface use;
2. It must account for its interaction with previous or planned future development in the subsurface;
3. It must consider its impact on the surrounding ecosystem services and the natural capital it provides.

The benefit of stage 1 is that it allows the use of the ground to be optimised for the use to which it is best suited based on its physical, chemical and biological properties. The benefit of stage 2 is that it reduces the possibility of potential conflicts in the subsurface. For example, it will reduce the chance of cool surface water being infiltrated into ground whose thermal properties make it more suitable for the installation of open loop ground source heat pumps for heating. It will minimise the impact of cavern development, desiccation of archaeological deposits through dewatering or overexploitation of water or thermal resources from multiple, individual uses. Stage 3 considers the environmental impact on surrounding ecosystem services whose function is reliant on the properties of the ground. The Stage 3 approach is similar to an Environmental Impact Assessment (EIA).

Each individual intervention is subject to the relative dominance or influence of drivers of development which may determine the use and type of use of underground space. Economic, environmental, political, social or technological drivers may make the use of underground space more or less likely. Each of these drivers is subject to change and some understanding of the possible future scenarios, is required to make truly sustainable future decisions about the use of the ground.

Geohazards and geoassets

The future use of the ground requires an approach that it is optimised for multiple uses based on an assessment of its geological, geotechnical, geomechanical and hydrogeological properties and their interaction with the range of ecosystem services and natural capital it provides.

The assessment of the suitability of the ground for a given subsurface use could be derived from published or newly acquired data and information where it is available. A vast array of invasive and non-invasive techniques are available for the investigation of the subsurface and its properties and a useful review of them is provided by de Mulder et al., (2012). Geological, engineering geological and hydrogeological maps and 3D geological models are often used to provide an initial assessment of the likely properties of the ground and their variability. This information may be supplemented by field and laboratory derived data, whose tests and analysis are specific for the intended use of the ground. Techniques including rock mass characterisation and numerical modelling allow the likely behaviour of the subsurface and its interaction with subsurface structures such as tunnels to be calculated.

The evolving use of applied geology maps is described by Culshaw and Price, (2011) and Ellison et al., (1998). They highlight that geological maps and their derived information developed from single-use applications such as mineral resource assessment, to multi-thematic uses for a range of purposes including hazard avoidance, excavatability and contamination. Increasing use of multi-thematic applied geology maps and information resulted in greater appreciation of the variability of the properties of the ground and its potential impact on land-use development (Ellison et al., 1998). Similarly, 3D geological models, often classified according to their lithological, stratigraphical, hydrogeological or geotechnical properties, are increasingly used for ground investigation planning and to minimise the risk of encountering unforeseen ground conditions or reducing the vulnerability of aquifers to pollution (Culshaw, 2005; Ford et al., 2008; Lelliott et al., 2006; Merritt et al., 2007; Price et al., 2010; Royse et al., 2009a; Royse et al., 2006; Royse et al., 2009b).

Maps, models, reports, data and information focus on the use of ground information for the avoidance or assessment of its susceptibility to the development of geohazards. In the UK deterministic hazard assessment algorithms have been applied to baseline digital 1:50 000 scale geological map data from DiGMapGB50 to derive national-scale geohazard maps in the form of the digital GeoSure Insurance Product (Booth et al., 2010; Foster et al., 2012; Walsby, 2008). Earth science information is commonly used to determine the hazard or risk associated with the exposure of urban populations to other global-scale hazards including, seismicity, volcanic eruption and flooding for example (McCall, 1996). Derived geoinformation on ground hazards provides a basis from which to assess the suitability of land (and its subsurface) for development through the avoidance of ground that may be associated with geotechnical hazards including landslides, shrink-swell clays and compressible deposits.

Of equal importance is the assessment of the ground in terms of its compatibility to deliver the function with which it’s compatible. De Mulder and Pereira, (2009) used the term ‘geoasset’ to describe the beneficial function provided by the ground as a consequence of its properties and the processes that operate within it. The beneficial function includes benefits to society or the environment. Geoassets can include provision of groundwater, mineral resources, attenuation of air, water and pollutants through soils, energy and drainage. Marker, (1996) recognised the use of earth science information for identifying opportunities for use of the ground in land-use planning. Where maps, models, data and information can be used to assess compatibility of the ground with its intended function, those data could be considered in an assessment of ecosystem service potential. For example, engineering geological maps showing geotechnical characteristics including strength, rock mass rating (RMR) and excavatability show the assets of the ground that are likely to allow it to perform the function for which it was designed. Digital datasets such as the national-scale infiltration SuDS map (Dearden and Price, 2012) and the shallow geothermal potential of the UK can be considered in the same way (Busby et al., 2011; Busby et al., 2009). Subsurface land-use suitability maps have been developed in the Zuid-Holland region of the Netherlands based on an assessment of the geological, geotechnical and hydrogeological properties of the ground (Wassing and van der Krogt, 2009).

Importantly, a compatibility assessment also allows potential conflicts in use to be identified. If there is competition for multiple uses of subsurface, could options to combine them be considered, either now or in the future? Some conflicts may exist which may not be easily resolved. This could include the potential for cavern or basement construction and burial of wastes on groundwater quality and flow or discharge of cool surface water into ground source heat systems reliant on the ground's thermal potential. An assessment of the positive or negative interactions between subsurface space use is therefore required in subsurface space planning. A framework for the optimisation of multiple uses of the subsurface based on its geological properties has been proposed for the Netherlands (de Mulder et al., 2012). This methodology is based on an assessment of the conflicts or benefits derived from the geological resource potential of the subsurface including mineral resources, groundwater, waste storage and geothermal energy.

The assessment of geohazards and geoassets using earth science data and its derived geoproperty information provides the first step in the assessment of the compatibility of the ground with its intended function. Recognition of its function(s) and its impact on other benefits that may be derived from other ecosystem services in the subsurface provides a means to avoid potential conflicts in use, provide multiple benefits and to deliver a sustainable solution, now and in the future. This process already happens, especially in relation to large-scale subsurface use including carbon dioxide sequestration, burial of solid and liquid wastes and civil engineering. It may not be as widely used in the urban environment where pressures of space usage may result in uses of the ground that may be incompatible with their properties.

Urban Futures

Lombardi et al., (2012) point out that large investments are currently being made to make our cities more sustainable. Sustainability considerations and their performance are more straightforward to apply to those solutions placed above the ground. It is more difficult to assess and measure their performance below the ground (Jefferson et al., 2009) where they may be out of sight and difficult to access and maintain. Whilst sustainability decisions made today (e.g. SuDS, brownfield regeneration, ground source heat systems) often consider their likely performance or impact into the future based on current trends, they do not readily consider the potential for the future to unfold in different ways (Rogers, 2009).

An assessment of a proposed use of the subsurface against possible scenarios of future development is rarely undertaken but could be beneficial when it is applied to the use of the ground beneath cities. Testing the robustness of a decision against a range of future scenarios provides a methodology to determine the long-term performance of the function (its ecosystem service) for which the intervention is designed. If the robustness of the decision can be tested against future scenarios, the resilience of that function could also be determined. The ultimate aim of applying a future scenarios assessment is to provide a solution today that delivers its benefits regardless of how the future might unfold.

A futures methodology for the assessment of sustainability solutions to the year 2050 has been developed for the UK with wider application to Organisation for Economic Cooperation and Development (OECD) countries (Lombardi et al., 2012; Rogers et al., 2012). The Urban Futures methodology recognises that there are many facets of the urban system which enable it to function in a similar way to the concept of urban metabolism recognised by Kennedy et al., (2007). The main facets of the urban system which operate together to deliver its core functions (its metabolism) are illustrated in Fig. 4. Collectively, they define sustainability themes that can be investigated and tested in the urban environment. The themes include ecology and biodiversity, water and wastewater and social needs, aspirations and planning policy. The function and trends within each of these facets are subject to changes reflecting variation in population, economy, environment, equity, technology and degree of conflict. The relative changes of selected criteria defining them can be used to analyse possible trends that characterise each of the future scenarios. They focus on those factors of change that affect urban land-use and city design and could be considered complimentary to an assessment of other forms of change including climate.

Four future scenarios have been defined through an extensive review of available global futures literature (Gallopin et al., 1997; Hunt et al., 2011; Raskin, 2005). These scenarios provide a narrative that allows the different possibilities of how the future might unfold to be explored. The scenarios are named Fortress World, Market Forces, Policy reform and New Sustainability Paradigm. The future scenarios and their defining characteristics are described in detail in Lombardi et al., (2012) and Rogers et al., (2012) and an example is shown in Table 3. Progressing from Fortress World, through to New Sustainability Paradigm, each scenario is characterised by increasing trends towards more sustainable use of resources and greater social and economic equity. Each scenario is further defined by relative changes and trends in factors including social mobility, social equity, land-use and individual and societal consumerism and behaviour.

The Urban Futures methodology begins by identifying a proposed urban intervention (a design, construction or sustainability solution) and its intended benefit. Examples of solutions include the construction of a multi-utility tunnel, rainwater harvesting to reduce demand on potable water supplies and installation of infiltration SuDS to reduce surface-water flooding. The conditions needed for that solution to continue to deliver its benefit (its ecosystem service) into the future are then identified. The conditions necessary for a rainwater harvesting system to continue to function include; continued demand, enough water must be collected to meet the demand, and it must be acceptable to the community (Lombardi et al., 2012). Each condition needed for it to deliver its future ecosystem function is then assessed against each of the criteria defining each scenario. This exercise reveals which conditions may be highly likely to exist, at risk or highly unlikely to continue into the future.

The ideal result is that each condition is highly likely to exist, regardless of how the future might unfold. It may be the case that some or all of the conditions are at risk in different future scenarios. It helps by providing an objective assessment of the resilience of sustainability solution into the future. It provides a qualitative assessment of the ability of the solution to function if it is subjected to social, technological, economic, environmental and political change. Secondly, it provides an opportunity, at the earliest stage of design, to explore alternative options in design, construction or planning that may increase the robustness of the solution to future change. If this is implemented, the urban futures methodology can provide a qualitative measure of sustainable solution resilience.

Urban Sustainable Subsurface Use Methodology (USSUM)

Step 1 Assessing the beneficial function of the ground

The optimisation of the use of underground space beneath cities begins with the identification and classification of the ecosystems services and benefits provided by it or as a result of physical, biological and chemical processes operating within it. Key steps are summarised in Table 4. In many cases multiple benefits derived from the function of the subsurface may be provided now or in the future. In other cases, benefits may not yet be provided, either because the use of the resource hasn't been recognised or optimised, or the ability of its function to perform is impeded. Identifying and classifying the ecosystem function of the subsurface requires a wide-thinking approach in considering its current and potential future benefits. Functions may include the identification of ground properties with suitable 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).

Step 2 Optimisation

The second stage requires characterisation of the ground and its properties based on its suitability for the planned use. The assessment should be planned to consider the vertical and lateral variability in those properties at different depths and scales of interest. Heterogeneity within ground properties that are required to deliver its intended function and benefit are likely to exist from the micro (pore space) to macro scale. The assessment of heterogeneity must therefore be considered at a scale that is appropriate for its intended use. The outcome of this phase of characterisation is the recognition of ground-based geoassets and geohazards which will determine the ability of the ground to deliver its function at different depths.

The combined outcomes of stages 1 and 2 have three desirable outcomes in considering the future use of the ground beneath cities. Firstly, it will allow the ground to be used in the best way to deliver its function based on a consideration of the ground properties required to deliver it and to avoid geohazards which impact on it. Secondly, it provides a mechanism to assess the likelihood of potential negative or positive subsurface interactions of the proposed use. Thirdly, it provides a mechanism to undertake an assessment of its environmental impacts based on its effect on the delivery of the ecosystem services that have been identified.

Step 3 Future scenario analysis

To test the future sustainability of the proposed use and to determine any potential vulnerabilities of it to future social, technological, environmental, economic and political change, futures analysis can be applied. This provides a powerful means to make decisions about subsurface use today that will yield robust solutions into the future.

Step 4 Implementation

After consideration of the future resilience of one or more sustainability-solution pairs, implementation can take place with increased confidence. Implementation is likely to be influenced by policy, legislation and the resources available. The style of implementation might also be influenced by the age and development history of a city. Young, rapidly growing cities may require a different form of implementation compared to ones that have a long legacy of development over centuries or millennia.

Subsurface policy and management

The sustainable management of the ground beneath cities and the probable increasing use of its resources requires strong legislation, policy and the resources to manage it sustainably. Its management brings together all of the resources and mechanisms required to plan, design, implement and deliver a proposed solution for subsurface use. There is currently a lack of consistent legislation and management which integrates options for sustainable subsurface management into land-use planning and associated legislation. Current use of the shallow subsurface to around 10 m below ground level has often taken place without consideration of its potential interaction with other uses, resulting in dense use of space and often competing uses for space (Bobylev, 2009). De Mulder et al., (2012) provides a comprehensive review of the legal, legislative and policy factors affecting subsurface development, including ownership and spatial planning.

It is evident that legislation governing use of the subsurface is either implicit in existing environmental and land-use planning legislation, or it is dealt with on an individual-use basis, commonly related to use or protection of underground resources. For example, legislation in Europe governs the use of groundwater resources and contaminated land through European Directives and its adopted law in member countries. Deeper in the ground, similar legislation exists between countries who exploit natural resources through mining, subsurface extraction of hydrocarbons or waste disposal, many of these activities occurring beyond city limits. Subsurface use and planning is not widely integrated into land-use or environmental planning which is often focused on a 2-dimensional, above-ground approach to land-use apportionment. Among recommendations made by Bobylev (2009), incorporation of underground space planning into city master planning and recognising that the land-use planning should be 3-dimensional, have the highest potential to deliver effective future subsurface planning and delivery of urban sustainability.

Some countries have adopted subterranean management plans, especially where the geological resources of the subsurface make subsurface development achievable and where environmental or political drivers already exist. In Helsinki, Finland, all underground activities and plans are coordinated under its Helsinki Underground Master Plan. In rapidly growing cities in SE Asia including Singapore and Hong Kong, where land for development is scarce, underground development policies are being developed (Arup, 2009). Plans that determine suitability for use, its environmental and societal impact have been developed in addition to the implementation of mechanisms for storage, management and dissemination of subsurface data and information (Anonymous, 2009; Rönkä et al., 1998). This plan ultimately apportions space for development underground, strongly driven by suitable geology, rapid urbanisation and environmental considerations. A similar policy study has been investigated in the Netherlands (Monnikhof et al., 1999).

These overarching policies have so far focused on cavern and tunnel construction. There is now an opportunity to integrate environmental legislation and the objectives of sustainable urban design into subsurface planning. Making the best use of underground space so that it performs now and in the future, regardless of how the future unfolds requires fully integrated above and below ground planning into future land management decisions in the urban environment.

Conclusions

With most of the world's population growth expected to take place in cities, pressures on urban land-use, including the shallow geological subsurface to a depth of between 80 and 100 m, are increasing. Physical space in the shallow geosphere in many cities in the UK and around the world is already heavily exploited and is becoming increasingly congested. This congestion reduces the options for use of the ground and reduces its ability to deliver the beneficial functions which are expected of it. A methodology that combines subsurface characterisation, ecosystem service classification and future scenario analysis provides the basis for developing and implementing an Urban Sustainable Subsurface Use Methodology (USSUM).

Resources in the underground environment and the benefits that people derive from them in towns and cities are often undervalued. This results in part from the fact that those resources and benefits are buried and hidden from view during the daily lives of most people. They often only come to light when those resources or parts of the environmental system that supports them, goes wrong. This might include the effects of ground subsidence, surface water flooding, surface sealing and utility failure through mechanical breakage. In these cases, the benefits that society derives from the ground are then often visible as disruption to transport networks, street works and effects on the operation of businesses. The net effect is disruption and cost to society and economy. A mechanism is proposed here to reduce the chances of those effects occurring. Or if they do, information will be available to understand why, when and how.

Recognition of the multiple ways that society benefits from the environment, including using its subsurface, could be enhanced through its consideration in the context of ecosystem services. Although often considered in an ecological or biodiversity context, it is suggested here that the benefits that society derives from favourable ground properties, could be considered in the same context. Where the ground's geotechnical properties provide bearing capacity to support civil engineering structures or aquifers yield groundwater or surface water is infiltrated or thermal properties allow the exchange of heat, they should be considered in the future as subsurface ecosystem services.

This has two benefits. Firstly that future urban subsurface use is optimised on the basis of the ground properties most likely to deliver the function it was designed for. Secondly those possible future positive or negative interactions between uses and functions of the subsurface are identified at the planning and design phase of a proposed subsurface intervention or land-use.

The future sustainability of cities and use of their subsurface relies on some assessment of how the future might unfold to understand its sustainability and resilience. Putting in place solutions that deliver benefits now and in the future requires some assessment of how the future might unfold. The Urban Futures methodology provides the framework to achieve it. Decisions about implementing sustainability solutions and using underground space can be made with increasing confidence by considering possible future scenarios of social, technological, economic, environmental and political changes. This could be enhanced through consideration of other forms of environmental change that might influence resilience, including climate. If the solution can deliver its benefits no matter how the future unfolds, it can be implemented with confidence. If the conditions required for the successful future function of a proposed use in underground space are threatened, what changes could be put in place to reduce the threat and increase sustainability and resilience? Futures analysis does not predict the future, nor does it attempt to map out a route to get there. The urban futures methodology provides a narrative that considers possible future changes within the facets of the urban system that might affect the performance of a proposed solution including use of the subsurface.

The integrated approach described here, takes familiar concepts and attempts to use them to propose a future strategy for managing the geoassets within underground space. Each of these geoassets are present at different depths and operate across different scales in the ground. The support for, and management of, the implementation requires strong policy implemented through effective legislation. Improved knowledge of the benefits in the ground beneath cities will increase the chance of community engagement and support for underground space use now and in the future.

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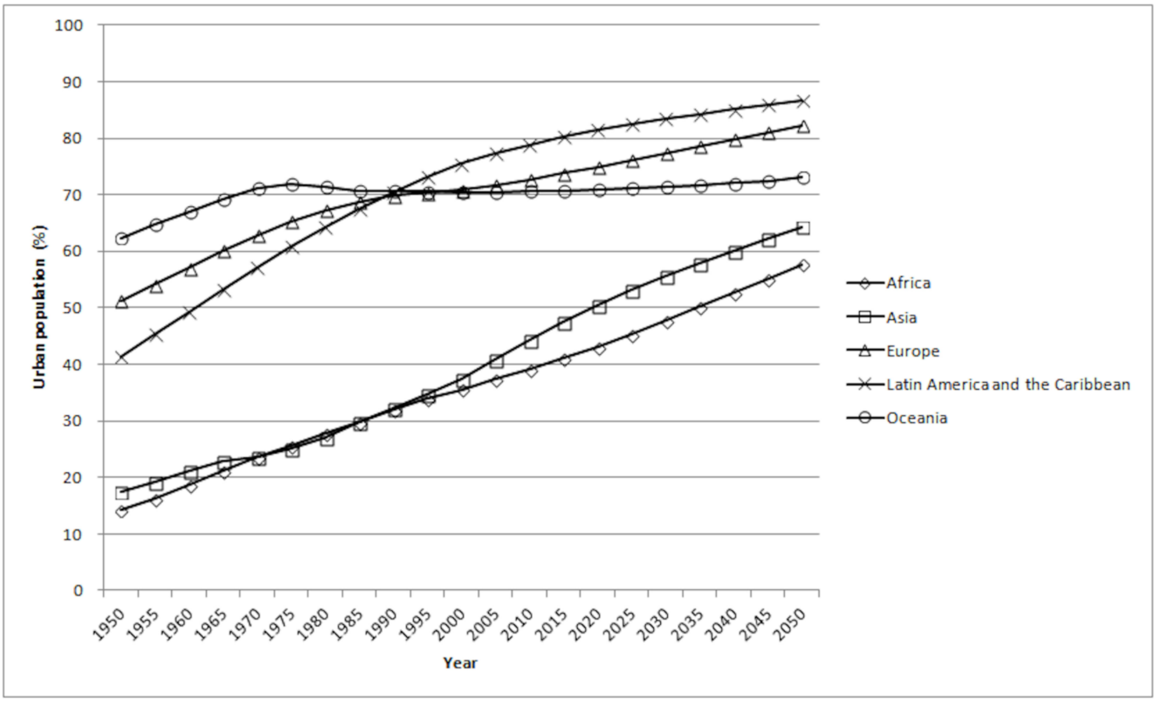

Fig. 1 Global urban population 1950 – 2050. Data from United Nations Department of Economic and Social Affairs Population Division (2012b)

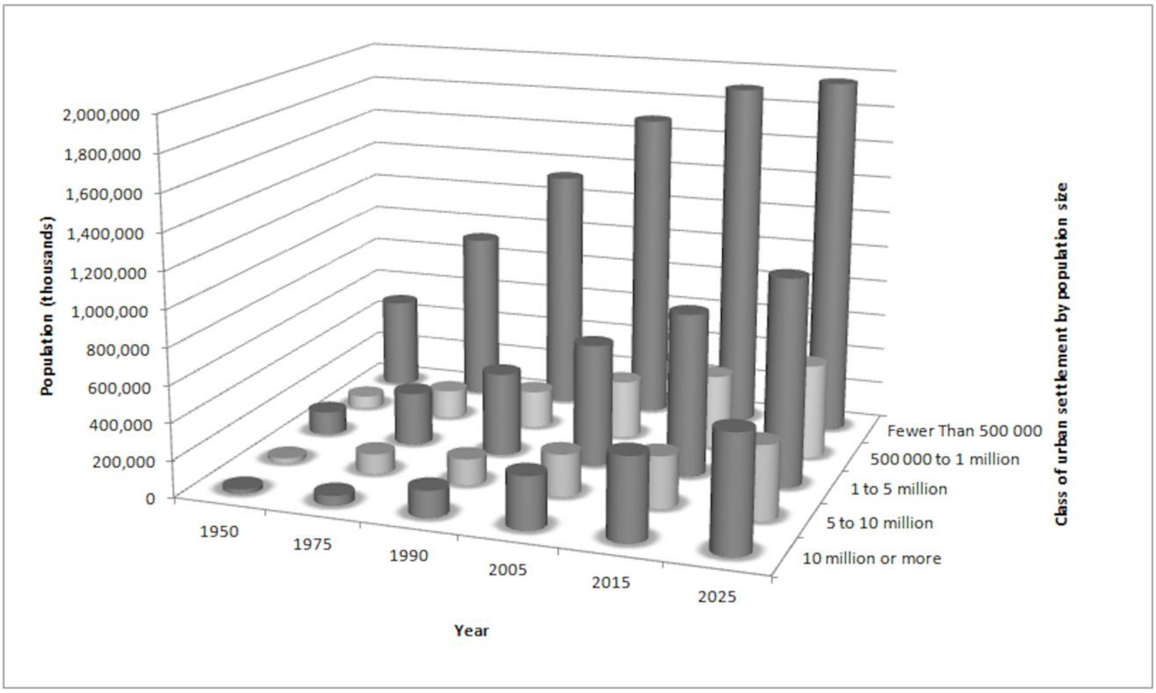

Fig. 2 Global urban population and their distribution between cities of fewer than 500 000, 500 000 to 1 million, 1 to 5 million, 5 to 10 million and 10 million or more. Data from United Nations Department of Economic and Social Affairs Population Division (2012b)

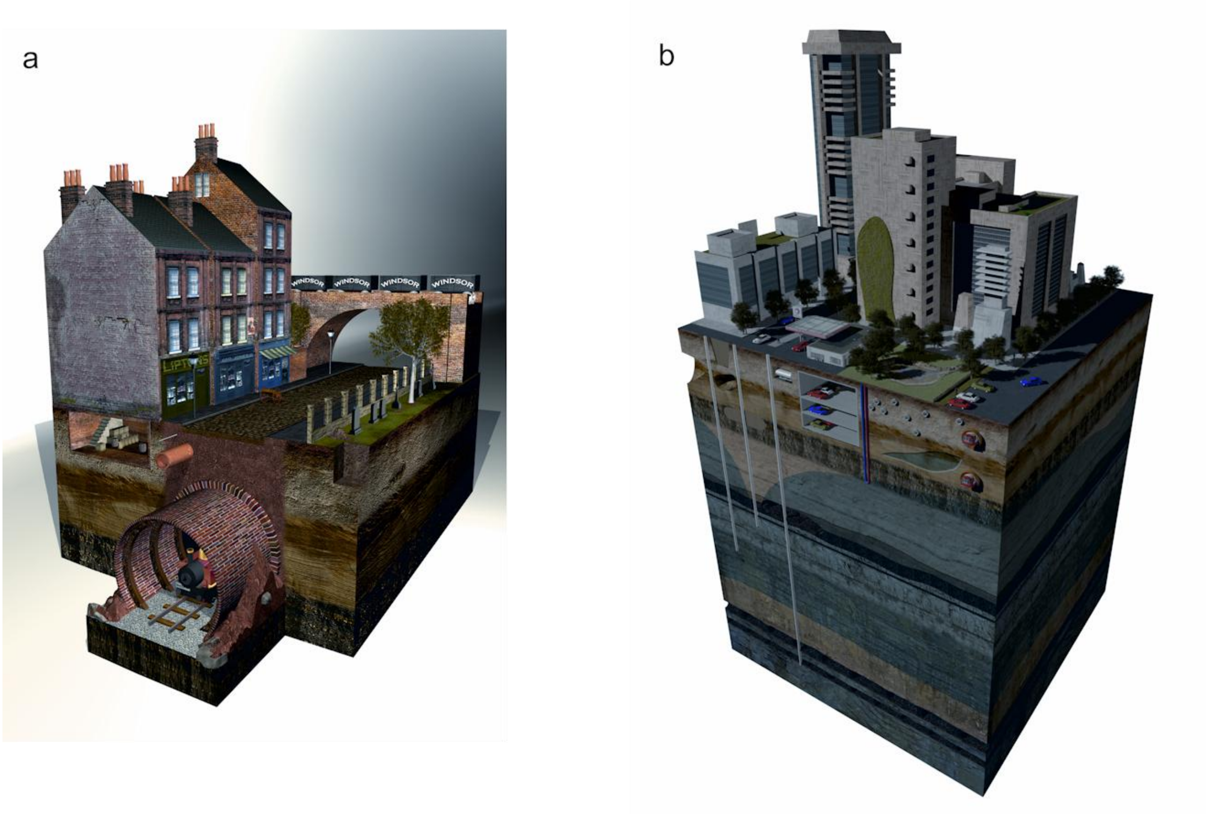

Fig. 3 Schematic illustration of the use of the urban subsurface through time for a hypothetical OECD country. a) Uses include construction of basements and shallow foundations, cut and fill for underground transport and drainage systems. b) Current and legacy uses including underground working for mineral resources, groundwater abstraction, multi-level underground transport, utilities and telecommunication networks, deep foundations and car parks and underground fuel storage

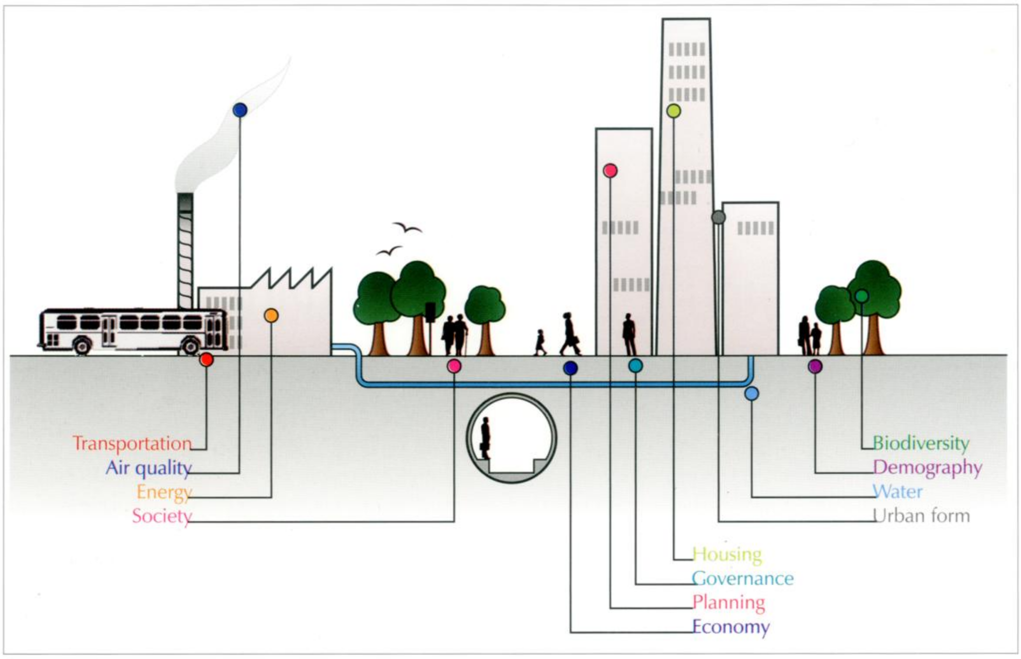

Fig. 4 Key facets of the urban system with which to measure its function. Each facet is subject to change as a result of social, technological, economic, environmental and political change. After Lombardi et al., (2012). Copyright IHS, reproduced by permission. The full publication may be purchased from http://www.brebookshop.com/details.jsp?id=326925

City	1970	1990	2011	2025
Tokyo, Japan	23.3(1)	32.5(1)	37.2(1)	38.7(1)
Delhi, India	-	-	22.7(2)	32.9(2)
Shanghai, China	-	-	20.2	28.4(3)
Mumbai (Bombay), India	-	12.4	19.7	26.6
Ciudad de México (Mexico City), Mexico	-	15.3(3)	20.4(3)	24.6
New York-Newark, USA	16.2(2)	16.1(2)	20.4	23.6
São Paulo, Brazil	-	14.8	19.9	23.2
Dhaka, Bangladesh	-	-	15.4	22.9
Beijing, China	-	-	15.6	22.6
Karachi, Pakistan	-	-	13.9	20.2
Lagos, Nigeria	-	-	11.2	18.9
Kolkata (Calcutta), India	-	10.9	14.4	18.7
Manila, Philippines	-	-	11.9	16.3
Los Angeles-Long Beach-Santa Ana, USA	-	10.9	13.4	15.7
Shenzen, China	-	-	10.6	15.5
Buenos Aires, Argentina	-	10.5	13.5	15.5
Guangzhou, Guangdong, China	-	-	10.8	15.5
Istanbul, Turkey	-	-	11.3	14.9
Al-Qahirah (Cairo), Egypt	-	-	11.2	14.7
Kinshasa, Democratic Republic of the Congo	-	-	-	14.5
Chongqing, China	-	-	-	13.6
Rio de Janeiro, Brazil	-	-	12.0	13.6
Bangalore, India	-	-	-	13.2
Jakarta, Indonesia	-	-	-	12.8
Chennai (Madras), India	-	-	-	12.8
Wuhan, China	-	-	-	12.7
Moskva (Moscow), Russian Federation	-	-	11.6	12.6
Paris, France	-	-	10.6	12.2
Osaka-Kobe, Japan	-	11.0	11.5	12.0
Tianjin, China	-	-	-	11.9
Hyderabad, India	-	-	-	11.6
Lima, Peru	-	-	-	11.5
Chicago, USA	-	-	-	11.4
Bogotá, Columbia	-	-	-	11.4
Krung Thep (Bangkok), Thailand	-	-	-	11.2
Lahore, Pakistan	-	-	-	11.2
London, United Kingdom	-	-	-	10.3
Seoul, Republic of Korea	-	10.5	-	-

Table 1 Population of global megacities (millions) in 1970, 1990, 2011 and 2025. (1), (2) and (3) denote the top three most populous megacities in each year. Data from United Nations Department of Economic and Social Affairs Population Division (2012b)

Category of ecosystem service	Examples of ecosystem service and their goods
Supporting	Soil formation Nutrient cycling Primary Production Habitat space
Regulating	Climate/Temperature (air quality, soil quality) Flood control Disease control Water (attenuation of quality and quantity) Noise
Provisioning	Food (allotments) Water supply (drinking and industrial use) Wood and fibre Energy Carbon store/regulation
Cultural	Aesthetic Spiritual Educational Recreational and tourism Archaeological Sense of place
Platform[1]	Support for development (above and below ground space, bearing capacity) Electrical earthing

Table 2 Categories of ecosystem service defined by the Millennium Ecosystem Assessment and the United Kingdom National Ecosystem Assessment (UK National Ecosystem Assessment, 2011; Corvalan et al., 2005), with emphasis on the urban environment. [1]Platform category not included as a category in the MEA or UKNEA. Category added to reflect the geotechnical service provision that enables functions including foundation support, after Rawlins et al., (2014)

Step 1. Identify sustainability solution and its intended benefit e.g. SuDS – reduce flood risk				
Step 2. Identify necessary conditions				
Step 3. Determine the performance of the necessary conditions in the future under each scenario				
Necessary conditions	**New Sustainability Paradigm**	**Policy Reform**	**Market Forces**	**Fortress World**
Land dedicated to SuDS	High-density development and urban village settlement patterns make implementation and maintenance of SuDS difficult. Small green spaces within the development may be appropriate	Strong planning controls are applied which recognise ecological and social imperatives and protect the functioning of SuDS	Weak planning policy may result in replacement of SuDS with other types of land-use where land is valuable. Economic arguments will dominate	Protection of SuDS inside rich enclaves for their amenity values; outside they might be converted for other uses as land is valuable
Regular maintenance for most pre-treatment designs	Maintaining sustainable infrastructure is both a community and governmental priority	Maintaining sustainable infrastructure is a governmental priority and is enforced through policy	Limited public funding available for maintenance unless there is a direct economic benefit	Money for maintenance available in rich enclaves, but not in poor areas outside the fortress
Catchment area remains of an appropriate size	Land-use will not change much due to high-density development so SuDS function well	Land-use will not change much due to compact development so SuDS function well	Urban sprawl tends to be dispersed giving space for SuDS solution	Urban sprawl inside rich areas increases the size of catchment area, rendering SuDS solution insufficient. This is not an issue for the high-density poor
Solution is socially acceptable	Highly acceptable solution since people prioritise sustainable resource management	Variable acceptability, but wide uptake, as dictated by policy	Low acceptability since the need for behavioural change has not entered peoples' consciousness and sustainability is not a core value	High acceptability as security of supply is important inside and outside the fortress

Table 3 An example of the Urban Futures methodology applied to sustainable drainage systems (SuDS). Modified after (Lombardi et al., 2012)

Step	**Objective**	**Comment**	**Drivers**
1	Determine **functions** of the urban subsurface that deliver **ecosystem services** and the benefits derived from them.	Functions can be categorised and assessed as an ecosystem service providing environmental natural capital and classified using the categories of provisioning, supporting, regulating, cultural and platform	Social, technological, environmental, economic (including cost-benefit analysis), political
2	Plan for optimised use of the ground based on its properties including geological, hydrogeological, geothermal and geotechnical Identify **geohazards** and **geoassets.** Avoidance of unsuitable ground conditions. Use of most suitable ground, delivering multiple benefits where possible.	Identify current or future positive or negative impacts and interactions of planned uses of the subsurface.	
3	Determine **sustainability** and **resilience** of a proposed intervention in the ground using **futures analysis** by identify sustainability solution-befit pairs.	Modify plans based on likely presence of the necessary conditions required for the solution to perform into the future.	
4	Implementation of proposed subsurface intervention.	Implementation is based on an assessment of performance against likely futures, minimising environmental impact and optimising use of space with appropriate properties to deliver its function.	

Table 4 Proposed stages in an Urban Sustainable Subsurface Use Methodology (USSUM). Decision-making in each stage is influenced by social, technological, economic, environmental and political drivers of change