Dublin city geo-environmental challenges as addressed by Geological Survey Ireland

Urban Environmental Challenges

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ABSTRACT

Understanding the geological framework is a fundamental component of sustainable development. Developments that fail to adequately accommodate the underlying geological conditions have the potential to compromise human health and be detrimental to economic and cultural well-being. This is particularly important in urban areas where; the density of development is greatest; exposure potential is high; history of intensive land-use is long and; access to sample and measure heterogeneous geological material is limited.

Systematic, integrated geoscience data on the urban environment is required for the protection of human health in urban areas, compliance with environmental legislation, land-use planning, brownfield remediation and urban regeneration.

Geological Survey Ireland produces urban geoscience data informing the areas of topsoil geochemistry and contamination, geological mapping and 3D modelling of ground conditions, and assessing terrain motions as a hazard in the urban environment.

Topsoil is of particular significance to the quality of urban environments and well-being of inhabitants. Topsoil geochemistry and contamination is mapped in Dublin to support Local Area Planning by Dublin Local Authorities.

Construction of city-scale geological models of the subsurface of Dublin provide a geological framework that facilitates informed planning and infrastructural decision making in urban areas.

Integrating remote sensing techniques and geological data to delineate zones of potential and observed terrain motion provide insights into building foundation, basement and tunneling conditions.

A perennial challenge for Geological Survey Ireland is to ensure that scientific data and information is delivered to key stakeholders in a format suitable for inclusion in the decision making process in order to enable the sustainable use of natural resources.

KEYWORDS

Natural resources, geological hazard, geological 3D-model, urban soil, geochemistry

1 INTRODUCTION

Urban geology brings together multiple traditional geoscience disciplines in order to inform the planning and management of the urban environment. It addresses the risks and opportunities associated with the subsurface, at a time when cities are intensifying land use by growing upwards and downwards by necessity to accommodate rising population. There are numerous definitions of urban geology in the literature, many focussing on urban geology as an applied, engineering-focussed sub-discipline which addresses the properties of the subsurface as hazards to built infrastructure. These definitions neglect the value of urban environments, and their contribution to human wellbeing and capacity to sustain human civilisations. This aspect is captured more comprehensively by Culshaw and Price (2010) in the definition of urban geology as: “The study of the interaction of human and natural processes with the geological environment in urbanised areas, and the resulting impacts, and the provision of the necessary geo-information to enable sustainable development, regeneration and conservation”.

This definition also includes the critical link of communication – the provision of information across the divides between scientists and the other relevant stakeholders in the urban environment. Our subsurface is a substrate for sustaining ecosystems but it has also come to be seen as an exploitable resource (for space, water, heating, cooling) and a hazard (seismic activity, subsidence, etc) in urban areas (Venvik *et al.*, 2018). However, to planners and policy-makers the subsurface is ‘out of sight, out of mind’ and it is the job of geologists and engineers to understand and communicate the nature of the subsurface so it can be managed and exploited sustainably for urban development.

Geological Survey Ireland is the national geoscience data provider and is part of Government of Ireland’s Department of Communications, Climate Action and Environment. For national Geological Surveys, urban geological data is provided by existing national mapping programmes which map bedrock geology, subsoil and groundwater resources. However, the opportunities to make the observations needed to create a geological map under a city are limited by soil sealing, the presence of made ground, the covering of natural rock exposures and reduced opportunities for exploratory drilling due to hardstanding surfaces, buildings and infrastructure. Hence in certain parts of cities confidence on the nature of subsurface conditions may be lower than desired. Conversely, certain areas of cities have been subject to intensive ground investigation related to recent development and may be mapped and modelled to a very high level of understanding. This heterogeneity in the quantity and quality of urban geological data needs to be addressed and communicated in a systematic way to data users.

Urban geological data differs from traditional mapping because it deals with the interactions of the natural world with human activities. The urban subsurface is a record of both geological processes and human ones such as habitation (as evidenced by archaeological heritage), industrial activity (chemical contamination), land reclamation (made ground), landscaping (engineered landforms) and mining (historical shafts) (Venvik *et al*., 2018). Urban geology is truly multidisciplinary, drawing on established disciplines of pure, applied environmental and engineering geology, but also requires an understanding of historical geography, city planning, urban sustainability and public health and the ability to communicate across disciplines.

2 DRIVERS FOR SUBSURFACE URBAN DEVELOPMENT

The use and reuse of urban underground space is becoming more attractive and necessary due to population growth, rising land values, advances in construction techniques and changes in planning regimes. The urban subsurface also has an important role to play in smart and sustainable city development as geothermal energy, and energy storage in the subsurface, can help us meet increasing energy needs whilst reducing our carbon emissions. Worldwide, the physical expansion of cities is increasing at a rate 1.5 times that of population growth (United Nations Statistics Division, 2019). The population of Dublin City grew by 5.6% from 2011 to 2016, to 1.73 million (Central Statistics Office, 2017). Policy is addressing the need for cities to grow sustainably within existing urban footprints.

2.1 POLICY

Sustainability is a key theme of EU and national policy relevant to the urban environment and the development of the subsurface (Table 1). Existing urban environments including the subsurface will play a key role in meeting the needs of current and future generations.

Policy	Relevant goal
Our Sustainable Future (Government of Ireland, 2012)	Goal 1: Improving the planning system so that future population and employment growth will have to predominantly take place in sustainable compact urban areas or rural areas which discourage dispersed development and long commuting.

Sustainable Development Goals National Implementation Plan 2018-2020 (Dept. Communications, Climate Action and Environment, 2018).	Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable. Indicator 11.6: By 2030, reduce the adverse *per capita* environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.
Project Ireland 2040 National Development Plan 2018-2027 (Government of Ireland, 2018)	To secure the sustainable growth of more compact urban and rural settlements supported by jobs, houses, services and amenities, rather than continued sprawl and unplanned, uneconomic growth. The €2bn Urban Regeneration and Development Fund for the five cities and larger urban centres will incentivise brownfield redevelopment and urban regeneration. The planning process will play a key role in realising the potential of the extractive industries sector by identifying and protecting important reserves of aggregates and minerals from development that might prejudice their utilisation.
Transport Strategy for the Greater Dublin Area 2016-2035 (National Transport Authority, 2016)	Proposes three major infrastructure projects to meet increasing demand for public transport and to address the limitations of the road network – MetroLink (underground metro), Bus Rapid Transit and DART (electric rail) expansion.

Table 1 - National policy relating to urban development

Despite this policy and planning framework, there is little or no specific treatment of soil and the subsurface in Irish policy, planning and legislation. Soil, as a critical resource, generally enjoys few of the protections afforded to air and water under EU and national policy. There is currently no specific contaminated land policy in Ireland and therefore no legislation in place to deal with it (Environmental Protection Agency, 2016). However, there are several legal instruments on agriculture, water, waste and chemicals which act indirectly upon soil in an uncoordinated manner. While the EU Commission in May 2014 decided to withdraw the proposal for a Soil Framework Directive, the Seventh Environment Action Programme, which entered into force on 17 January 2014, recognises that soil degradation is a serious challenge (European Parliament *etc.*, 2013). It acknowledges the unsustainable use of fertile land (1,000 km^2 of land per year taken for development) and soil degradation (half a million contaminated sites) in the EU. It calls for a 'land degradation-neutral world' and for soil quality issues to be addressed using a risk-based approach within a legally-binding framework at Member State level.

There is an absence of underground planning policy in Ireland. Several cities (Oslo, Helsinki) have adopted subsurface 'masterplans' to allow for the harmonious development of the subsurface within existing natural and built constraints (Venvik *et al.*, 2018). Common recommendations of such masterplans include the compulsory entry of site investigation data into state-run databases; the amendment of property databases to allow for three dimensional entries (basement records); and planning permission requirement for the use of potentially conflicting subsurface resources (groundwater, geothermal energy, basement space). Although Dublin lacks an underground planning masterplan, some elements are being advanced; these are described here.

2.2 PLANNING GUIDELINES

A number of recent planning regime changes will have the effect of increasing the requirement for high-quality information on the physical and chemical properties of the subsurface, through the reuse of brownfield land, deeper foundations associated with taller buildings and increased basement development. Geological Survey Ireland is a statutory consultee for certain developments concerning the geological environment as well as a data provider.

The Guidelines on Urban Development and Building Heights for Local Authorities (Dept. Housing, Planning and Local Government, 2018) aim to support the accommodation of population growth and development in urban areas by building up (allowing for taller buildings), effectively lifting arbitrary and blanket building height regulations which have historically been in place in the planning regime. The guidelines are set to encourage street-level development in city and town centres to six storeys as the default objective and taller buildings in areas with suitable enabling infrastructure (Dept. Housing, Planning and Local Government, 2018). The guidelines also place emphasis on reusing brownfield land. Dublin City Council is currently considering rezoning up to two thirds of Dublin’s business and light industry-zoned land for residential housing (Kelly, 2019). Permission has recently been granted for the construction of 3,500 new homes in a new urban quarter on Dublin’s Poolbeg peninsula, a reclaimed brownfield area of current and historical industrial (CAAS Ltd, 2017). The development, which is underlain entirely by artificial ground, including landfill in places, will include a strategy for underground services and utilities and an underground waste water plant. The use of these brownfield sites for residential and amenity development will require characterisation of the quality of the land and risk assessment in support of the change of land use.

In recent years, there has been a significant growth in new basement development and extensions to existing basement accommodation (Dublin City Council, 2016). The Dublin City Local Authority Development Plan restricts basement development in zones of flooding, conservation and archaeological interest; and permits basement development with regard to a range of considerations including impact on the water table (Dublin City Council, 2016). Dublin City Council is currently developing a new policy to formalise the planning requirements for basements, requiring Basement Impact Assessment in relation to groundwater flow and other considerations.

3 CHALLENGES FOR SUBSURFACE DEVELOPMENT

3.1 COST AND QUALITY OF URBAN SITE INVESTIGATIONS

Insufficient understanding of subsurface ground conditions places significant constraints on effective and sustainable development of urban areas, and is a key factor in overspend on construction projects (Bonsor *et al.*, 2013). Uncertainty is inherent in relation to ground conditions, given that the number and extent of observations of the subsurface is limited e.g. trial pits, boreholes or other excavations. A number of factors give rise to insufficient understanding of subsurface ground conditions, including lack of mapped data, poor availability and quality of existing site-specific data and poor communication between scientists and key stakeholders in the development of the urban environment: planners, developers, consultancy (civil, structural and environmental) and the public.

Reducing uncertainty about ground conditions results in an improvement in risk management for construction projects and considerable cost savings and efficiency gains in planning and development (Paul *et al.*, 2002). For highway construction projects, traditional levels of expenditure on site investigation (typically <1%) are associated with cost overruns of up to 100%, while expenditure of 6% on site investigation appears to be necessary to guarantee an overspend of less than 10%. Clayton (2001) notes that in order to reduce cost and increase certainty relating to ground conditions, the emphasis should be on effective use of existing information and expert opinion, supported by ground investigation. The importance of desk-study reconnaissance including published geological information as a prerequisite to site investigation is also emphasised by the British Standards Institution in its BS5930 Code of Practice for Ground Investigation (British Standards Institution, 2015).

3.2 DATA AVAILABILITY

Data on the urban subsurface which is purpose-designed, quality-controlled and systematically-collected data is in short supply and is difficult to acquire. Many subsurface observations are collected as part of private sector site-specific investigations for a particular purpose, with variable quality and quantity of relevant observations. This data is usually not easily available, as it has proprietary value to consultancies and is often confidential to the original client.

Geological Survey Ireland manages the National Geotechnical Borehole Database (NGBD), a freely-accessible archive and web viewer which holds data on over 7,500 site investigations nationally, sourced from private and public sector developments. The NGBD is an important national asset which is supporting the reuse of subsurface data for infrastructural development; however submission of site investigation is not compulsory or in accordance with standardised data formats. Other national Geological Surveys have developed their site investigation data repositories by enforcing legislative requirements for the private and public sectors to submit data in standardised formats, however this require significant resources to process the enormous quantity of resulting information. Geological Survey Ireland also hosts an online GIS-based map viewer, Geourban, which provides baseline geological information for Dublin city and derived products based on borehole observations (depth to bedrock and rockhead elevation).

3.2.1 3D MODELLING

Traditionally geological maps show a 2D representation of rocks at or near the ground surface. The third dimension of depth and the fourth dimension of time are becoming increasingly important considerations for the conceptual modelling of the subsurface where it underpins urban infrastructure. Geological Survey Ireland has developed 3D models of Dublin (Fig. 4) and Cork, allowing the wealth of 3D information in borehole records to be combined with existing 2D geological maps. The models were developed using Geographic Information Systems and 3D modelling software (Subsurface Viewer for subsoil and SKUA for bedrock), with the outputs visualised in 3D Adobe Acrobat PDF documents.

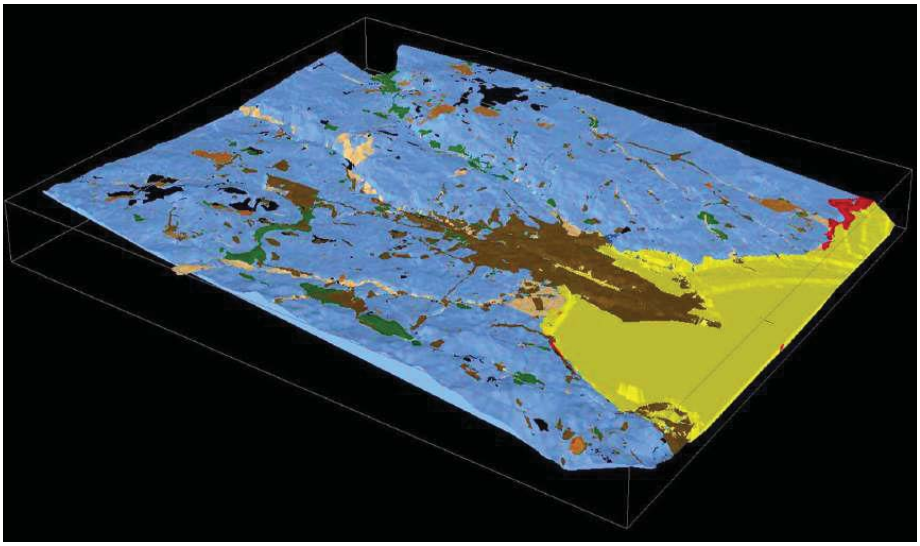

Figure 4. Quaternary sediments (subsoils) 3D model of Dublin (from Mozo Lopez *et al.,* 2012).

3.2.2 3D BUILDING INFORMATION MODELS

In 2011 the UK published a Building Information Management (BIM) strategy with the view to establishing 3D (subsurface) BIM requirements for government-funded construction projects. Ireland is at a less-developed stage with regard to BIM; the National Development Plan 2018-2027 (Government of

Ireland, 2018) provides for the creation of a Construction Sector Working Group to be established, which will examine matters such as the role of Building Information Modelling to improve productivity and efficiency.

3.2.3 MULTI-DISCIPLINARY COLLABORATION

There is a need at multiple scales to coordinate, deliver and support the use of relevant geoscientific information to stakeholders including planners, developers and the site investigation industry to support regional planning, desk studies and site investigations. Data quality and integration is not necessarily enough to optimise the use of subsurface data. It was found in Rotterdam and Glasgow that integrated, 3D Geographic Information System platforms were not enough to bind together the efforts of urban planners and subsurface practitioners – it was necessary for the two disciplines to work together directly to achieve an improvement in the urban planning process (Venvik *et al.*, 2018).

National Geological Surveys struggle to understand exactly what it is that users require and the users themselves do not appreciate how geology might be relevant to their particular problem (Culshaw and Price, 2010). Turner (2003; cited in Culshaw and Price, 2010) found that users of urban geoscience data were likely to be less able to interpret geological information, requiring it in different forms that were more understandable and related specifically to the problems for which they required solutions. This problem has been observed and borne out by Geological Survey Ireland in the development of various user-focused products such as Groundwater Protection Schemes (Dept. Environment and Local Government *et al.*, 1999) for planners and Tellus geochemical mapping for the agronomic sector (Lark *et al.*, 2014). Novel communication techniques such as verbal probabilistic scales and legends for geochemical data employed by the BGS and GSI (Lark *et al.* 2014), convey uncertainty as an inherent part of the information, and link the geoscience data to action responses appropriate to the user. This reduces the prospects of misuse and misinterpretation of the data, but requires iterative, focused engagement with each targeted stakeholder and a considerable, dedicated effort. Culshaw and Price (2010) note that to adequately communicate geological information and knowledge about the urban environment it is necessary to:

- Understand institutional and decision-making structures;
- Disseminate as well as present;
- Tailor outputs to audiences;
- Use communication experts;
- Work with social scientists.

4 DUBLIN'S SUBSURFACE ENVIRONMENT

It has been suggested that the ideal geological setting for a city is on flat, solid, low-radiation rock; beyond main seismicity zones; far from volcanoes and at least 20m above sea level (de Mulder and Pereira, 2009). Ireland's urban areas fare relatively well in relation to major geological hazards, being sited far from high seismicity zones and volcanoes on a passive Atlantic tectonic plate margin. However, the hazards of naturally radioactive rock giving rise to radon exposure, and the risk of freshwater flooding and seawater inundation in many Irish urban areas are well known and present significant challenges for public health/safety and economic development. Dublin is located is located on Ireland's eastern coastal margin and occupies an area of 920 km². Dublin is situated at the mouth of the River Liffey. It is bordered by a low mountain range to the south and surrounded by flat farmland to the north and west (Figure 1).

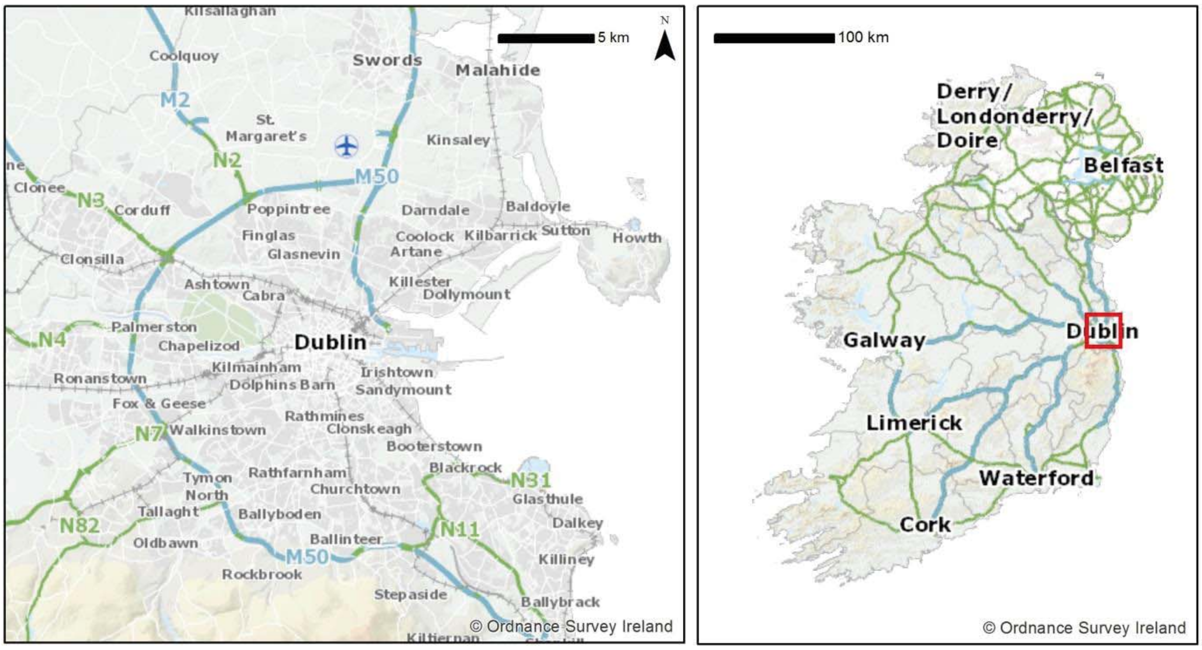

Figure 1. Dublin is located on Ireland's east coast, north of the Wicklow Mountains and on the estuary of the River Liffey.

4.1 ROCK

Dublin city is underlain by the Dublin Basin, a geological region composed of Lower Carboniferous age (*c.* 325-345 million years old) limestones and shale, known colloquially as Calp (McConnell, 1994) (Fig. 2). Dublin Bay is confined by the granite headland of Dalkey to the south and the quartzite peninsula of Howth in the north (McConnell, 1994). The city is bounded in the south by the upland Leinster granite region of the Wicklow mountains.

The Dublin Calp remains relatively poorly understood in terms of composition and structure, due to limited opportunities to observe the bedrock in urban areas. The strength of the rock can vary from weak to very strong (Farrell and Wall, 1990). Due to its high shale content the limestone is generally not prone to the development of cavities like pure limestones are; however, layers of weathered clay/mudstone in the rock can give rise to localized problems bearing weight such as building foundations (Farrell and Wall, 1990). Apart from some road cuts and historical quarries, Dublin's bedrock is completely covered by a thick layer of subsoil. The rock surface under the subsoil is not a smooth surface and there exists a variable, broken, weathered and decomposed zone between the subsoil and bedrock known as the transition zone. Geological Survey Ireland has been undertaking mapping of the bedrock and subsoil of Ireland since its foundation in 1845. Recent work has focused on the characterization of transition zone, as its geotechnical and aquifer properties are often different to both the subsoil and the bedrock.

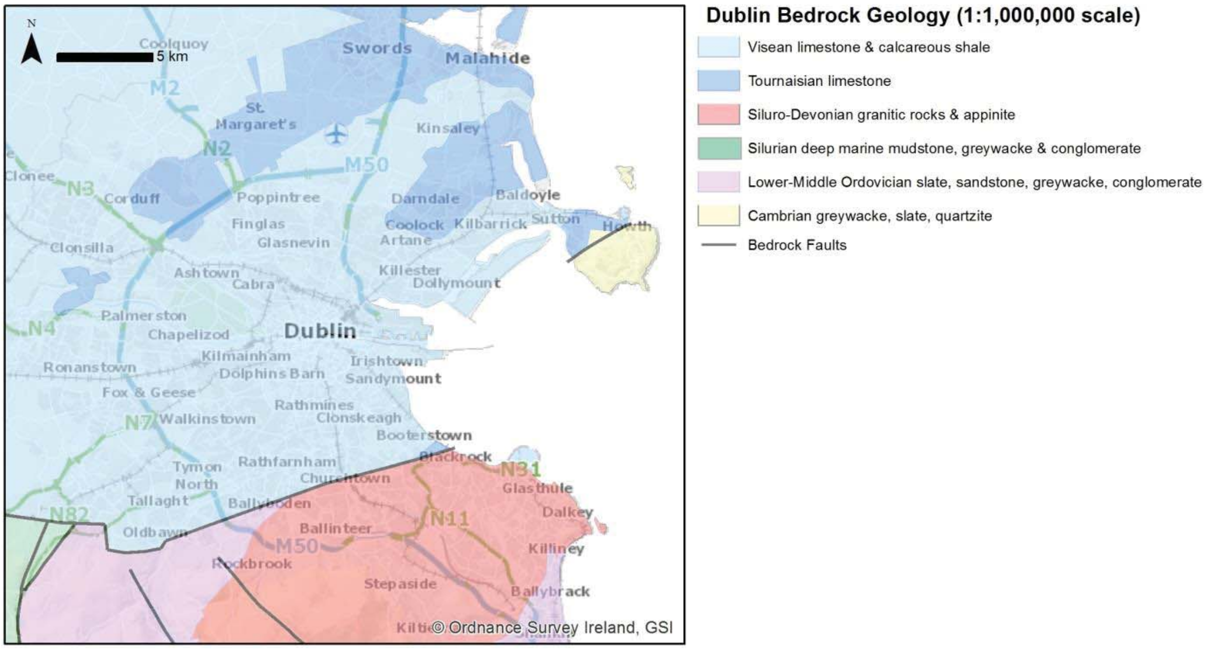

Figure 2. Bedrock Geology of Dublin (source: Geological Survey Ireland Geological Map Series 1 Million Scale).

4.2 SOIL AND SUBSOIL

Historically urban soils have been systematically under-represented in primary resource surveys due to the difficulty of observing them, leading to critical information gaps (Cummins *et al.*, 2018a). Geological Survey Ireland's Quaternary Sediments map (Pellicer, 2018) delineates the parent materials of Dublin's soil and subsoil types, by recording textural, morphological and other information (Fig. 3). The map also delineates the known extent of 'urban' or anthropogenic soil. However, given the paucity of appropriate data, coupled with the inherent diversity of the physical properties of anthropogenic soil, no description or classification of its properties have been attempted to date. In the greater Dublin area, there are extensive glacial sediments or subsoil overlying bedrock, consisting of widespread boulder clay or till (stiff clay with cobbles/boulders) of varying thicknesses (in the order of up to tens of meters) and areas of thick alluvial and glacial sand and gravel along the River Liffey channel. In places, the till and alluvial gravels are interspersed, making it difficult to map definitive soil zones.

Such complex unconsolidated deposits are the main medium within which construction, excavation and tunnelling take place in the city and they have some challenging geotechnical properties by international standards. Investigations for the planned MetroLink underground rail megaproject have identified the boulder clay (presence of cobbles and boulders) and the gravel channel (coarse, dense, highly permeable and abrasive) as challenges for boring a 17km tunnel through Dublin's city centre (Friedman and O'Connor, 2019). The strength, compressibility and plasticity of the boulder clay are variable, and the presence of boulders means that it is difficult to recover good samples for testing during drilling of core (Farrell and Wall, 1990).

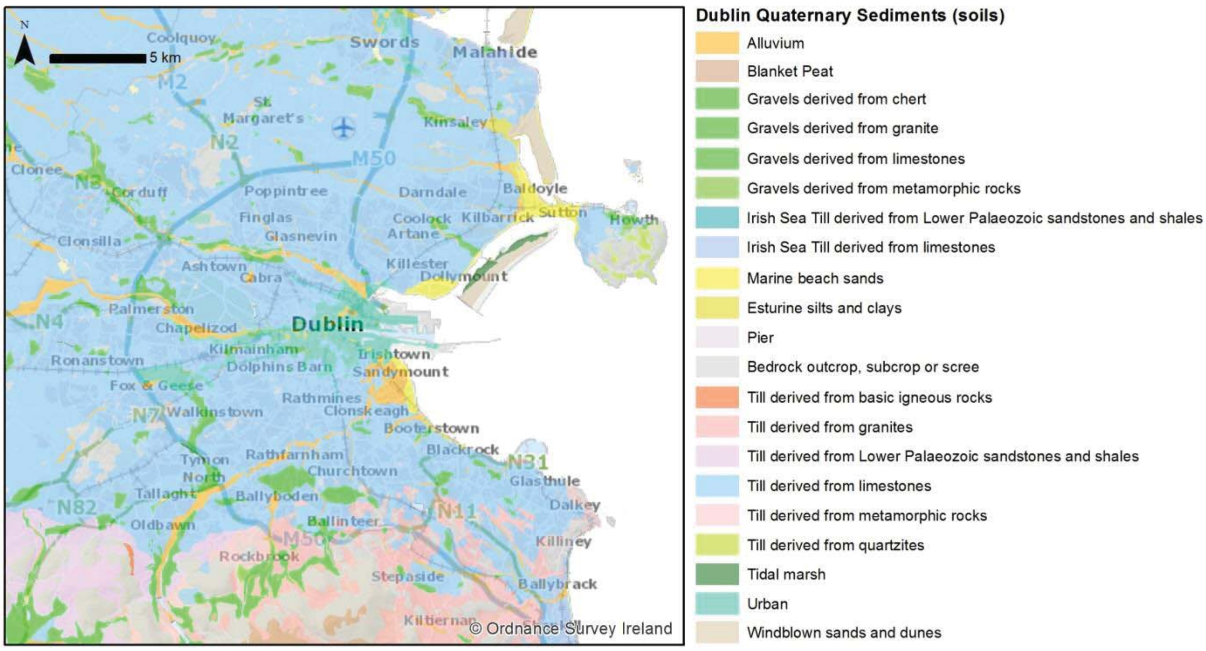

Figure 3. Quaternary sediments geology of Dublin (source: Geological Survey Ireland Quaternary Sediments map).

Much of the soil in Dublin's inner city has been subject to human alteration through land reclamation and construction over 1,000 years of settlement. Urban soil which has been modified by human activity, also known as made ground, varies in its physical constituents, chemical properties and geotechnical properties. Chemical contamination and archaeology are often also relevant considerations for development. In cities, man's influence is often preserved in the geological record over millennia. Soils and sediments are the preservation environment for most archaeological remains, with a range of soil conditions influencing preservation including pH, particle size, moisture content, oxygen levels, redox potential, soil minerals, parent material, organic matter content and biota (Cummins *et al.*, 2018b).

Approximately 2% of the greater Dublin area is covered with made ground. Its presence is most commonly associated with the reclamation of low-lying coastal and estuarine ground in the modern day Liffey quays and docklands area, and in quarry voids around the city (Glennon *et al.,* 2012). Between 3 and 6m of fill was required to bring Dublin's intertidal zone above the high tide level to the region of 3.4m O.D, and Dublin's oldest area around Christchurch is underlain by up to 4m of made ground of archaeological significance (Farrell and Wall, 1990). Ash and clinker from the power generation and coal burning industries are known to have been used historically as fill in the docklands, port and low-lying inner city coastal areas. In 2015 Dublin City Council examined 135 parks and green spaces, finding that approximately one third had some form of landfill, imported or made ground: 18% were former landfills, 7% former quarries and 4% reclaimed wetlands (Cummins *et al.,* 2018a), based on limited historical information. The MetroLink investigations identify the presence of made ground in Dublin's inner city as a challenging ground condition for excavation and disposal, due to its anticipated contaminant content and largely unknown physical properties (Friedman and O'Connor, 2019).

Although Dublin was not industrialised to the same extent as Belfast or the industrial cities of England, it had a concentration of industry in the docklands related to shipping and processing of imported goods including fertilizer, timber, foodstuffs and coal. Geological Survey Ireland has mapped the geochemistry of Dublin's urban topsoil and commissioned a historical industry survey to gain an understanding of how past industrial activity may have affected soil quality in Dublin (Glennon *et al.*, 2012 and 2014). The project identified over 2,000 potentially contaminating historical industries (including chemical works, metals processing, oil/gas/coal industry and power generation) and showed that the concentrations of the heavy metals and persistent organic pollutants in Dublin's shallow soil are strongly influenced by human activities. Highest concentrations were observed in the docklands, inner city and heavy industry areas. Concentrations of other elements (e.g. arsenic) in topsoil in the greater Dublin area showed patterns which could be attributed to the natural bedrock properties in the region. It was recommended that an assessment of sediment quality be carried out in the River Liffey estuary, as major cities located on the lower reaches of rivers and estuaries can contribute significant loadings of contaminants into river and estuary sediments. Studies in Glasgow demonstrated that concentrations of persistent organic pollutants were up to 60 times higher in urban tributaries compared to the upper rural river environment (Fordyce and Campbell, 2019).

The absence of geochemical data for deeper subsoil (>1m below ground level) has emerged as a major data gap for the Dublin urban area. Systematically mapped subsoil geochemistry information is absent in Ireland, although limited site-specific information exists mainly in the private sector. Subsoil geochemistry is a significant consideration for major infrastructure projects involving the disposal or reuse of excavated urban soil. Depending on the individual case, excavated soil may be considered a waste, not a waste, or a by-product under the waste regulatory regime (Environmental Protection Agency, 2018) with significant economic costs and logistical challenges associated with the different designations. Geological Survey Ireland is currently assisting the Environmental Protection Agency (EPA) with developing an approach to managing the reuse of excavated subsoil and stone in Soil Recovery Facilities (unlined quarries/pits). The natural geochemical conditions at both the source and intended destination of excavated subsoil are critical considerations in management and licencing these sites for the protection of human health and the environment.

The mapping and modelling of all urban soils including anthropogenic deposits is essential to characterise the full range of subsurface conditions in urban environments (Culshaw and Price, 2010) and this remains a challenge for national Geological Surveys.

4.3 GROUNDWATER RESOURCES

Groundwater resources in Dublin are limited by both naturally modest aquifer potential, and from anthropogenic impacts on water quantity and quality, although small industrial, municipal and private abstractions within the city centre and suburbs are known (Mozo Lopez *et al.*, 2016). Public drinking water supplies for the Dublin region are derived predominantly from surface water, with the majority of water coming from the Vartry, Dodder and Liffey River catchments. Dublin lacks a groundwater level and quality monitoring network and opportunities exist to increase understanding of Dublin's aquifers to assess groundwater quantity and quality for drinking water supply, to understand climate-related groundwater level change, to manage flooding and to manage contaminated land. The transition zone, the broken, weathered and decomposed zone between the subsoil and bedrock, has been shown to be a significant groundwater pathway in areas such as Dublin underlain by poorly productive aquifers. The transition zone is a potential pathway for contaminant flow, and is currently the subject of investigation by Geological Survey Ireland under the GW3D project.

4.4 GEOTHERMAL ENERGY

The use of geothermal energy for both heating and cooling provides an opportunity for urban areas to meet increasing energy needs in the future and to lower reliance on finite hydrocarbon energy resources. In order to optimise energy usage, urban geothermal installations should ideally be connected to district heating systems as part of wider city plans. The recent growth of support for public district heating schemes in Irish cities (e.g., Dublin City and South Dublin County Councils funded by the Climate Action Fund 2018) provides an opportunity for geothermal heat to form part of the renewable energy mix in Irish cities and help to decarbonise the heat energy sector.

Dublin's subsurface is a proven resource for the development of deep and shallow geothermal energy. Ireland has widespread shallow (< 400 m) geothermal resources for small and medium-scale heating applications, and in 2015 Geological Survey Ireland published a suite of Geothermal Suitability maps to support uptake of geothermal heat pump applications. A notable example of large-scale commercial use of shallow geothermal heat is the installation at Ikea, Ballymun, North Co. Dublin, where a suite of 150 boreholes (each 120 m deep) combines to contribute 1.5 MW of heating and cooling. In order to increase the installed capacity of geothermal energy in urban areas, detailed subsurface information is required to establish the present thermal state, the potential of the resource to meet heating and cooling demands, and the possible locations and densities of geothermal energy installations (Epting, 2016). Geological Survey Ireland is a participant in the GeoERA MUSE (Managing Urban Shallow geothermal Energy) project to investigate resources and possible conflicts of use associated with the use of shallow geothermal energy in European urban areas.

Ireland has recognised potential for deep geothermal energy in areas of deep sedimentary rocks in the south and east, including the Dublin Basin. An industrial pilot project by GT Energy at Newcastle in Co. Dublin demonstrated a faulted geothermal reservoir with promising temperatures at depths in excess of 1.4 km. As result of this exploration a 5 MW geothermal power plant in Newcastle received planning permission, but the development was later shelved due to a lack of a regulatory framework. Geological Survey Ireland is assessing barriers to geothermal energy uptake in Ireland in pan-European consortia (GeoERA, GEOTHERMICA), and will produce a Geothermal Energy Roadmap for Ireland in 2019.

4.5 FLOODING AND COASTAL EROSION

Ireland's flood risk policy and measures are coordinated by the Office of Public Works, and flooding responses are coordinated on a government-wide level through the Interdepartmental Flood Policy Coordination Group, of which Geological Survey Ireland is part. The degree of urbanisation of a catchment is a significant risk factor for fluvial (river) and pluvial (rainfall runoff) flooding, due to sealed, relatively impermeable surfaces which encourage rapid overland flow. Dublin City Council estimates that over

20,000 buildings are at risk from flooding in Dublin city and another 10,000 are likely to become at risk, due to sea level rise, increased heavy rainfall and flooding (Kilraine, 2019).

Climate-related coastal flooding and erosion pose significant risk to coastal cities. Ireland's five main urban areas Dublin, Cork, Limerick, Galway and Waterford are sited on the coast. Geological Survey Ireland is undertaking a new initiative to map coastal vulnerability to climate-related sea-level rise. The project will aim to identify the coastal regions, including the Greater Dublin area, most likely to be affected by impacts of sea-level rise by using a coastal vulnerability index (CVI) approach. The CVI has been tested on a pilot study from Portrane to Arklow (Caloca-Casado, 2018). The first phase of CVI mapping (2019-2020) will map areas from north Co. Louth to Co. Wexford.

4.6 GROUND INSTABILITY

Ground instability can be caused by swelling clay, landslip, ground dissolution, running sand, collapsible or compressible ground. Geological Survey Ireland has assessed the potential for ground instability in Dublin and Cork as part of the EU FP7-funded PanGeo project using Radar satellite-derived measurements of ground and building movement, geological information and field validation. The main observed instability areas are associated with compressible ground. Some 33.5 km² (<4%) of Co. Dublin has potential or observed ground instabilities, mostly associated with peats of the Dublin Mountains (Sheehy and Verbruggen, 2013).

4.7 RADON

Radon is a radioactive element which occurs naturally in earth materials. Exposure to high concentrations of radon is known to increase the risk of lung cancer. In Ireland, the radon risk map is produced from indoor radon measurements by the Office of Radiological Protection of the EPA. Geological Survey Ireland is working with the EPA to understand and predict natural sources of radon in rocks, soils and waters nationwide, as part of the National Radon Control Strategy (Dept. Environment, Community and Local Government, 2014). Some of the highest indoor radon measurements found anywhere in Europe, are in Ireland. Radon is associated with certain naturally radiogenic rock types such as granites. However, high radon concentrations can occur in a variety of geological settings and are often associated with complex geological sources and transport pathways. In Dublin, up to 10% of homes are at risk of being above the reference level for radon. Geological Survey Ireland's Radon Working Group (consisting of geochemistry, geophysics and groundwater experts) is undertaking in-house projects and research partnerships in order to research the complex relationship between radon and geology, with the view to refining and predicting high radon areas in Ireland.

4.8 BUILDING STONE AND AGGREGATES

The quality and quantity of raw materials (stone and aggregate) available for construction is a determining factor in the rate of urban development. Given the large urban construction plans inherent in Project 2040 (Government of Ireland, 2018), demand for aggregate and building stone is set to increase, and there are a number of critical considerations in meeting this demand. Sourcing the right material in the right location is a challenge which is being addressed through the planning system and by Geological Survey Ireland. When existing infrastructure and incompatible land use is taken into account, a large percentage of Ireland's area is already unsuitable for raw material production (pits and quarries) and it is increasingly important that any remaining prospects are identified and sufficiently protected from being built over. This is particularly important in city hinterlands, as the carbon footprint of raw materials for construction is heavily influenced by transportation from source to destination. Given the projected increase in the cost of carbon, increasing transport distances will not only detract from efforts to reduce Ireland's climate impact but will also inhibit the effectiveness of the economy and the cost of construction. The urban streetscape contains buildings constructed with significant quantities of locally sourced dimension stone. These buildings frequently require repair or replacement of stonework and it is important that the stone used is matched as closely as possible to the existing material to ensure the preservation of the architectural and visual heritage.

Coherent planning and foresight is required to avoid a repeat of conditions whereby a significant unforeseen increase in aggregate demand may result in the production of sub-optimal material. The economic boom of the early-2000s resulted in the unsuitable use of aggregate containing deleterious materials such as pyrite and mica which has resulted in significant socio-economic problems necessitating the remediation of affected private dwellings and public buildings. Tackling these challenges will require a greater interaction between those with expertise of the subsurface and those charged with deciding on the development which takes place on the surface. Geological Survey Ireland has also begun work with local authorities to facilitate the generation of raw materials strategies which can be taken into account by planners based on projected demand. In relation to the sourcing of ornamental building stone, Geological Survey Ireland is participating in the Stonebuilt project with Trinity College and the Office of Public Works to create a national inventory of building stone, and in the GeoERA EuroLithos project which will result in an ornamental stone knowledge base for Europe.

5 CONCLUSIONS

There are increasing demands on high quality space in urban areas, and subsurface resources of space, water and energy will become increasingly important considerations for future urban planning and development. Compared to other cities worldwide, Dublin has limited subsurface development, although several major and mega-scale projects are set to bring the subsurface, and the importance of understanding and mapping it, into focus. Geological Survey Ireland provides a range of data and products relevant to subsurface investigations and research, but there exist opportunities to acquire new urban data, increase data availability and integration, and collaborate with other urban stakeholders to optimize use of subsurface environment information.

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BIBLIOGRAPHIC REFERENCES

Bonsor, H. C., Entwisle, D. C., Watson, S., Lawrie, K., Bricker, S., Campbell, S., Lawrence, D., Barron, H., Hall I. and Ó Dochartaigh, B. É. (2013) Maximising past investment in subsurface data in urban areas for sustainable resource management: a pilot in Glasgow, UK. Technical note. *Ground Engineering*, February 2013.

British Standards Institution (2015) *Code of Practice for Ground Investigations BS5930:2015.* BSI Standards Ltd.

CAAS Ltd (2017) *SEA Environmental Report Appendix II – Non-technical summary as part of preparation of the Strategic Development Zone Planning Scheme for Poolbeg West (S.I. no. 279 of 2016).* Report prepared for Dublin City Council.

Caloca-Casado, S. (2018) *Coastal vulnerability assessment of Co. Dublin and Co. Wicklow to impacts of sea-level rise.* ProQuest Dissertations Doctoral Publishing, Maynooth University, Ireland.

Central Statistics Office (2017) *Census 2016 Summary Results - Part 1* Central Statistics Office, Ireland.

City of Dublin. TU1206 COST Sub-Urban WG1 Report.

Clayton, C. R.I. (2001) Managing geotechnical risk: time for change? *Proceedings of the Institution of Civil Engineers, Geotechnical Engineering*, 149(1), 3-11.

Culshaw, M.G. and Price, S.J. (2010) The 2010 Hans Cloos lecture: The contribution of urban geology to the development, regeneration and conservation of cities. *Bulletin of Engineering Geology and the Environment*, 70(3), 333-376.

Cummins, T., Lewis, H., Ní Lionáin, C. and Davis, S. (2018b) *Soils and Archaeology.* In: Creamer, R. and O'Sullivan, L. The Soils of Ireland. Springer World Soils Book Series. Springer International Publishing, Switzerland.

Cummins, T., Myles, F., Scanlon, R., Glennon, M., Gallagher, V., Harris, M. (2018a) *Urban Soilscapes.* In: The Soils of Ireland. World Soils Book Series. Springer.

de Mulder, E. and Pereira, J.J. (2009) Earth Science for the City. In: Culshaw, M.G., Reeves, H. J., Jefferson, I. and Spink, T.W. (eds) *Engineering Geology for Tomorrow's Cities.* Geological Society, England.

Department of Communications, Climate Action and Environment (2018) *The Sustainable Development Goals National Implementation Plan 2018-2020.* Government of Ireland.

Department of Environment, Community and Local Government (2014) *National Radon Control Strategy.*

Department of Housing, Planning and Local Government (2018) *Urban Development and Building Heights. Guidelines for Planning Authorities.* Government of Ireland.

Department of the Environment and Local Government, Environmental Protection Agency and Geological Survey of Ireland (1999) *Groundwater Protection Schemes.* Government of Ireland, Dublin.

Dublin City Council (2016) *Dublin City Development Plan 2016–2022.Written Statement.*

Environmental Protection Agency (2016) *Ireland's Environment. An Assessment 2016*. Environmental Protection Agency, Ireland.

Environmental Protection Agency (2018) *Guidance on Soil and Stone By-products. Public Consultation.* [Online] Accessed: 26/04/19. Available at: http://www.epa.ie/pubs/consultation/Guidance_Art27_ByProduct_Soil_Stone_Consultation.pdf.

Epting, J. (2016) *Geothermal monitoring and modelling.* [Online]. Accessed 13/03/19. Available at: http://rotterdam.maps.arcgis.com/apps/MapJournal/index.html?appid=5f495157aae84a2780b5e7d87dcd66f2#

European Parliament and the Council of the European Union (2013) *Decision No 1386/2013/EU of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet'.* Official Journal of the European Journal 28.12.2013.

Farrell, E. and Wall, D. (1990) *Soils of Dublin.* Paper presented at a joint meeting of the Geotechnical Society of Ireland and the Institute of Structural Engineers, 10th October 1990.

Fordyce, F. M., & Campbell, S. D. (2019). The Geosciences in Europe's Urban Sustainability: Preface. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 108, 109-112.

Friedman, M. and O'Connor, E. (2019) *Metrolink: Some geotechnical challenges that lie ahead.* Presentation to the Geotechnical Society of Ireland seminar on Transport Tunnelling, Engineers Ireland, Dublin, 10th April 2019.

Glennon, M., Harris, P., Ottesen, R.T., Scanlon, R.P. and O'Connor, P. (2014) The Dublin SURGE Project: Geochemical baseline for heavy metals in topsoils and spatial correlation with historic industry in Dublin, Ireland. *Journal of Environmental Geochemistry and Health,* 36(2), 235-254. Special Issue on the 9th International Symposium on Environmental Geochemistry.

Glennon, M., Scanlon. R., O'Connor, P.J., Finne, T.E., Andersson, M., Eggen, O., Jensen, H.K.B., Ottesen, R.T. (2012) *Dublin SURGE Project. Geochemical baseline for heavy metals and organic pollutants in topsoils in the greater Dublin area.* Geological Survey of Ireland report.

Government of Ireland (2012) *Our Sustainable Future. A Framework for Sustainable Development for Ireland.* Government of Ireland.

Government of Ireland (2018) *Project Ireland 2040. National Development Plan 2018-2017.* Government of Ireland.

Kelly, O. (2019). Dublin industrial estates to be transformed for housing. *Irish Times*, 26th February 2019.

Kilraine, J. (2019) Flood risk for 20,000 Dublin city buildings, council says. *Irish Times*, 16th February 2019.

Lark, R.M., Ander, E.L., Cave, M.R., Knights, K.V., Glennon, M.M. and Scanlon, R.P. (2014) Mapping trace element deficiency by cokriging from regional geochemical soil data: a case study on cobalt for grazing sheep in Ireland. *Geoderma*, 226–227, 64–78.

McConnell, B. (ed). (1994) *Geology of Kildare-Wicklow. 1:100,000 scale Bedrock Geology Map Series, Sheet 16.* Geological Survey of Ireland.

Mozo Lopez, B., Sheehy, M. and Hunter Williams, T. (2016) *Subsurface and urban planning in the City of Dublin.* COST TU1206 Sub-Urban Report.

National Transport Authority (2016) *Transport Strategy for the Greater Dublin Area 2016 – 2035.* National Transport Authority, Ireland.

Paul, T., Chow F.C., Kjekstad, O., Vahaaho, I., Sellberg, B., Haegeman, W., Lemos, L., Sleffert, J.G., Bucher, F., and Feda, J. (2002) *Hidden aspects of urban planning: surface and underground development.* Thomas Telford Publishing, London.

Pellicer, X. M. (2018) *Geological Survey Ireland Physiographic Units Map of Ireland.* Geological Survey Ireland report.

Sheehy, M. and Verbruggen, K., 2013. *PanGeo - Geohazard description for Dublin.* Geological Survey of Ireland, Dublin, Report D7.1.25, 11/02/2013.

United Nations Statistics Division (2019) *High Level Political Forum Goals in Focus. Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable.* Available at: https://unstats.un.org/sdgs/report/2018/Goal-11/. Accessed: 20/02/19.

Venvik, G., Liinamaa-Dehls, A., and Bjerke, C. (2018) *Pathways & pitfalls to better sub-urban planning. COST Action TU1206 Sub-Urban.* NGU Geological Survey of Norway.