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The role of engineering geology in delivering the United Nations Sustainable Development Goals

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Abstract: Engineering geology has an important role to play in sustainable development. This is due to the unique perspective that engineering geologists have of the interfaces between: science and engineering; the natural and built environments; the past, present and future. This paper examines the role of engineering geology in delivering the United Nations Sustainable Development Goals (SDGs) and demonstrates that there is a strong link between the knowledge, skills and activities of engineering geologists and the delivery of all 17 goals. The study includes a detailed evaluation of all 169 SDG targets and highlights the key impact areas where engineering geologists already contribute to sustainable development, as well as identifying opportunities for contributions to be strengthened. It is hoped that this paper will empower engineering geologists to confidently communicate the value of their role, act responsibly and exert their influence to drive positive outcomes in terms of sustainable development in everything that they do.

Supplementary material: Mapping exercise of typical engineering geology knowledge, skills and activities against all 169 SDG targets and related indicators is available at https://doi.org/10.6084/m9.figshare.c.5778817

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The concept of sustainable development is widely considered to have been formalized by the 1987 Brundtland Report (Sachs 2015; Shi *et al.* 2019; IISD 2021; Sachs *et al.* 2021) where it was defined as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (WCED 1987). This report proposed the establishment of a United Nations (UN) programme on sustainable development resulting in a succession of international frameworks including Agenda 21 (UNCED 1992), the Millennium Development Goals (United Nations 2000) and, most recently, the Sustainable Development Goals (SDGs) (United Nations 2015).

Over time, these frameworks evolved and the emphasis on future generations was replaced by socially inclusive, environmentally sustainable and economically viable development (Basiago 1999; Sachs 2015; Mensah 2019; Cisneros-Montemayor *et al.* 2021; Sachs *et al.* 2021). This 'three pillars' model, which seeks to balance social, environmental and economic sustainability, is often referred to as 'People, Planet, Profit' or the 'Triple Bottom Line' (Elkington 1994). More recently, a foundational fourth pillar, referred to variably as culture, politics, institutions or governance, has also been introduced to reflect the importance of wellbeing, ethics and dignity in sustainable development, and the role of organizations in its delivery: for example, through the introduction of Environmental, Social and Corporate Governance (ESG) with finance and business practice (Hawkes 2001; Littig and Grießler 2005; UCLG 2010; Burford *et al.* 2013). Achieving sustainable development is complex, requiring solutions to a wide range of issues and recognizing that trade-offs may be needed. Challenges hindering pathways to sustainable development (e.g. food insecurity) or threatening development gains (e.g. climate change) must be viewed from diverse perspectives to find equitable and balanced solutions. Both individual and collective action are required to harmonize the four pillars and avert environmental and social disaster (IGS 2019).

Engineering geologists have a key role to play, in applying their unique knowledge and skills, and offering their own perspectives to help tackle global sustainable development challenges. The contribution of engineering geology to *some* of the UN SDGs has already been highlighted in publications such as Gill (2017), Cook (2019), Dottridge and Smith (2020) and Geological Society of London (2020), as well as to the preceding Agenda 21 framework by Nathanail (2013). This paper seeks to go further by demonstrating that engineering geologists can make a meaningful contribution to *all* of the UN SDGs through their projects, initiatives and institutions.

The United Nations SDGs

The UN SDGs were set out in the 2030 Agenda for Sustainable Development (UN Resolution A/RES/70/1), which was adopted by all UN member states in 2015. There are 17 SDGs (Fig. 1) supported by 169 targets and 231 unique indicators to allow measurement of progress. The goals collectively aim to eradicate extreme poverty, end unsustainable consumption patterns, and facilitate sustained and inclusive economic growth, social development, and environmental protection (United Nations 2015). Covering a broad policy

Fig. 1. The United Nations Sustainable Development Goals (United Nations 2022).

agenda, the UN SDGs were developed in consultation with hundreds of thousands of participants and a range of stakeholder groups, including the science and engineering communities.

The 2030 Agenda for Sustainable Development makes clear that the 17 UN SDGs are global in nature and should be applied universally (United Nations 2015). While some previous development frameworks focused exclusively on developing countries (so called ‘Global South’), the goals and targets are relevant to all nations. Realizing the transformational vision set out in Agenda 2030 depends on societies from all stages of development status collectively achieving all of the UN SDGs. The governments of the UN Member States are responsible for implementation, embedding the goals and targets into their nation’s policies and strategies, and monitoring progress.

Agenda 2030 emphasizes that the UN SDGs are an integrated and indivisible framework for sustainability. The interdependencies between the natural and built environment, social and economic systems are complex (Nilsson *et al.* 2016; International Council for Science 2017; Allen *et al.* 2019). If not considered in an integrated way, positive progress towards one goal could unintentionally hinder progress towards others. Therefore, a holistic strategy for addressing the UN SDGs is required to maximize progress towards all goals and minimize trade-offs (Singh *et al.* 2018; Bryan *et al.* 2019). Focusing too narrowly on specific goals and targets must be avoided (Allen *et al.* 2019; Goubran 2019; Maes *et al.* 2019; Moyer and Bohl 2019).

A number of other UN frameworks have been developed to complement and support delivery of the UN SDGs. For example, the Sendai Framework for Disaster Risk Reduction 2015–30 aims to reduce disaster risk and losses (aligned to SDG 11 (Sustainable cities and communities)) (UNDRR 2015*a*); the Paris Climate Change Agreement aims to enhance the implementation of the United Nations Framework Convention on Climate Change (aligned to SDG 13 (Climate action)) (UNFCCC 2015); and the New Urban Agenda (Habitat III) aims to support well-planned and well-managed urbanization (also aligned to SDG 11) (United Nations 2017). The UN also support delivery of the SDGs through their other programmes such as the UN Environmental Programme (UNEP) and the UN Office for Disaster Risk Reduction (UNDRR).

Geoscience, engineering geology and the United Nations SDGs

Science, technology and innovation each play a key role in achieving the UN SDGs (Gluckman 2016), with a number of the targets recognizing the need to strengthen the science–policy interface. Geoscientists possess deep domain knowledge of natural systems and processes that makes them very well placed to tackle the environmental issues covered by the UN SDGs. This understanding is required for the monitoring, protection, management and restoration of the natural environment (Lubchenco *et al.* 2015; Gill 2017; Gill and Smith 2021). However, despite their unique skills and knowledge, geoscientists have historically been under-represented in the global debate on sustainable development (Mora 2013; Stewart and Gill 2017). A significant opportunity therefore exists for geoscientists to increase their influence and enhance their impact.

The contribution of the various subdisciplines of geoscience to the UN SDGs is discussed in Gill (2017) and illustrated by the *Geoscience for the Future* poster published by the Geological Society of London (2020). These depictions highlight the contribution of engineering geology to SDG 1 (No poverty), SDG 2 (No hunger), SDG 7 (Affordable and clean energy), SDG 8 (Decent work and economic growth), SDG 9 (Industry, innovation and infrastructure), SDG 11 (Sustainable cities and communities) and SDG 13 (Climate action). *Geosciences and the Sustainable Development Goals* (Gill and Smith 2021) provides the most comprehensive review of geoscience in the context of the UN SDGs to date, with a focus on engagement through academia and education. While these publications capture the range and diversity of the contribution of geoscience to the UN SDGs, none of them examine in detail the role and skills of engineering geologists. Five years after the Brundtland Report, and more than two decades before the UN SDGs were launched, the role of engineering geology in solving environmental problems caused by human activities and in building resilience to natural hazards had already been recognized by the International Association for Engineering Geology and the Environment (IAEG) in their definition of engineering geology as

> [T]he science devoted to the investigation, study and solution of the engineering and environmental problems which may arise as the result of the interaction between geology and the works and activities of man as well as to the prediction and of the development of measures for prevention or remediation of geological hazards
>
> (IAEG 1992).

This definition also articulates that engineering geology embraces the application of geomorphology, hydrogeology, geomechanics and geochemical characterization (IAEG 1992).

Reflecting on the themes of the IAEG congress' and main symposia over the past 20 years suggests the industry itself recognizes the importance of its role in addressing many of the issues covered by the UN SDGs, including the impacts of climate change, territory protection, population safety, landscape exploitation, sustainable urbanization, infrastructure development, material use, education and preservation of cultural heritage (IAEG Congress, 2002–2003, 2005–2006, 2011, 2013–2014, 2018). The 2006 IAEG Congress session on the future of engineering geology also recognized that engineering geologists need to improve how they communicate the value of their contribution to sustainable development (Baynes *et al.* 2009). Despite this broad recognition, there has been limited practical holistic guidance to enable practitioners and researchers specifically engaged in engineering geology to understand how they can, or already do, contribute to sustainable development in the context of the 17 UN SDGs. A recent search of publicly available literature, conducted by the authors of this paper using the WorldCat database (https://www.worldcat.org accessed in 2021), found only a single relevant publication (Cook 2019) containing the words 'engineering geology' and 'sustainable development goals' in the title, and a further nine relevant publications where 'engineering geology' and 'sustainable development goals' were identified as keywords (Brandolini *et al*. 2018*a*, *b*; Bohle 2019; Doyle *et al.* 2019; Fordyce and Campbell 2019; Hosseini *et al.* 2019; Kyaw *et al.* 2019; Osinubi *et al.* 2019; Reid *et al.* 2019).

This paper seeks to address a gap in the literature by providing engineering geologists with a clearer understanding of how they already contribute to the UN SDGs, as well as identifying opportunities to strengthen their contribution. It is envisaged that this paper will enable engineering geologists to understand the consequences of their work in terms of sustainable development, empower them to communicate confidently the value of their role and to exert their influence to drive positive outcomes on their projects.

Methodology for mapping engineering geological knowledge, skills and activities to the UN SDGs and targets

In order to understand fully the current contribution of engineering geologists to the UN SDGs, and where this could be enhanced, a mapping exercise was undertaken to review systematically all 169 SDG targets and related indicators against typical engineering geology knowledge, skills and activities. Similar exercises for other geoscience and engineering disciplines have been undertaken previously, but none specifically relating engineering geology to SDG targets; these include:

(1) high-level mapping of geoscience subdisciplines to the UN SDGs by Gill (2017) and the Geological Society of London (2020), which focus on the goals rather than targets and indicators;

(2) high-level mapping of the UK Sustainable Remediation Forum (SuRF-UK) indicator categories against UN SDGs by Bardos *et al.* (2011, 2018), which focuses exclusively on contaminated land management;

(3) a more in-depth mapping of geophysical applications and practices to all 17 of the UN SDGs by Capello *et al.* (2021) using expert elicitation, which similarly does not make an assessment at target level; and

(4) detailed mapping of construction-related activities and the UN SDGs, including individual targets and indicators, undertaken by Czerwinska (2017), Alawneh *et al.* (2019), Goubran (2019), *The Economist* Intelligence Unit (2019) and Gyadu-Asiedu *et al.* (2021). These assessments identify direct dependencies between the construction industry and some of the SDGs, in addition to indirect dependencies of all other SDGs. Goubran (2019), in particular, provides a rigorous methodology to assess holistically the interlinkages of all goals and targets.

The methodology applied to this mapping exercise is largely adapted from Goubran (2019) with modifications to make it appropriate to engineering geology. The mapping involved identification of targets that are dependent on engineering geology knowledge, skills and activities to realize their ambitions through a direct contribution, or indirectly via delivery of other targets. Table 1 presents the dependence definitions adopted in the review, as well as examples to illustrate how this approach was applied. Direct contributions have been subdivided into primary and secondary dependencies as outlined in Table 1. All direct dependencies and some indirect dependencies, where relevant, are supported by case examples where the contributions can be demonstrated through a project or initiative, or through relevant literature. Where possible, opportunities to strengthen the contribution of engineering geology to individual targets were also identified.

The mapping exercise used the authors' collective experience and judgement (covering multiple sectors, geographies and project types). This heuristic approach (Capello *et al.* 2021) was preferred over a systematic quantitative literature review (Pickering and Byrne 2014) because there are too few publications (11 in total) with 'engineering geology' and 'sustainable development goals' identified as keywords; and it was also considered important to capture the typical practice of engineering geologists working in industry, which is often not documented in the academic literature. As a consequence, the analysis will include some subjectivity and generalization: for example, the need to strengthen contributions may vary in different contexts (e.g. by country) and evolve over time; and only addresses whether we have identified a link to an SDG target, and not the relative strength of this link.

For the purpose of this mapping exercise, the discipline of engineering geology was restricted to the typical role and activities undertaken by engineering geologists within industry and academia. While this does, and always will, include some necessary overlap with other disciplines – in particular hydrogeology, geotechnical engineering, geo-environmental engineering, mining engineering, petroleum engineering and engineering geophysics – we have not considered the totality of the roles and activities undertaken within these disciplines.

Results

The results of the analysis demonstrate that engineering geologists can contribute to all 17 of the UN SDGs. Engineering geology knowledge, skills and activities can be directly linked to 82 of the 169 targets (48%) and indirectly to a further 25 targets (15%). Of

Table 1. *Dependence definitions used to map engineering geology knowledge, skills and activities to the UN SDGs and targets, including examples of application*

Dependence	Definition	Example
Direct (Primary)	Targets that depend on engineering geology activities to realize their ambitions, in all contexts. A clear, direct contribution that engineering geologists make and that is essential to the widespread achievement of the target	Target 3.9 – by 2030: substantially reduce the number of deaths and illnesses from hazardous chemicals, and air, water and soil pollution and contamination – delivering this target will require effective ground characterization to understand both natural and anthropogenic contaminants and potential pathways to receptors
Direct (Secondary)	Targets where the engineering geology community have direct responsibility for implementing change or sustaining good practice within their sector	Target 10.6: ensure enhanced representation and voice for developing countries in decision-making in global international economic and financial institutions in order to deliver more effective, credible, accountable and legitimate institutions – the engineering geology community operate with international organizations, such as the IAEG, and have direct and sole responsibility for how inclusive they are
Indirect	Targets that depend on engineering geology activities realizing another target	Target 3.1 – by 2030: reduce the global maternal mortality ratio to less than 70 per 100 000 live births – delivering this target is dependent on the delivery of other targets, such as Target 6.1 (clean water) and 6.2 (safe sanitation and hygiene), as well as Target 9.1 (quality, reliable and resilient infrastructure). Infrastructure clearly contributes to the realization of many targets but also has its own goal
No contribution	Targets that are independent of engineering geology activities	Target 3.5: strengthen the prevention and treatment of substance abuse, including narcotic drug abuse and harmful use of alcohol – no obvious link between engineering geology knowledge, skills and activities and the delivery of this target

those that are directly dependent, 44 (26%) are of primary dependence and 38 (22%) are of secondary dependence (see Table 1 for dependence definitions). The results of the analysis are presented in Table 2, as well as in Figure 2a in terms of the number of targets and in Figure 2b in terms of the percentage of the total number of targets, and are discussed in further detail below. The full results of the mapping exercise are provided as part of the Supplementary material for this paper; summaries of mapped targets are also provided in Table 2.

Engineering geology makes the strongest overall (both direct and indirect) contribution to: SDG 7 (Affordable and clean energy), where it is linked to 100% of the targets; SDG 9 (Industry, innovation and infrastructure), where it is linked to 88% of the targets; SDG 12 (Responsible consumption and production), where it is linked to 82% of the targets; and SDG 11 (Sustainable cities and communities) and SDG 13 (Climate action), where it is linked to 80% of the targets for both goals.

Engineering geology makes the strongest direct (both primary and secondary) contributions to SDG 7 (Affordable and clean energy), SDG 13 (Climate action) and SDG 11 (Sustainable cities and communities), where it is directly linked to 80% of the targets for all three goals. It also makes a strong contribution to SDG 12 (Responsible consumption and production), where it is directly linked to 72% of the targets, as well as to SDG 6 (Clean water and sanitation) and SDG 9 (Industry, innovation and infrastructure), where it is also directly linked to 63% of the targets for both goals.

Engineering geology makes the strongest primary direct contributions to: SDG 7 (Affordable and clean energy), where it is directly linked to 80% of the targets; SDG 11 (Sustainable cities and communities), where it is directly linked to 70% of the targets; SDG 6 (Clean water and sanitation), where it is directly linked to 63% of the targets; and SDG 13 (Climate action), where it is directly linked to 60% of the targets.

Engineering geology makes the weakest overall contributions (direct and indirect) to: SDG 10 (Reduced inequalities), where it is linked to only 20% of the targets; SDG 14 (Life below water), where it is linked to 40% of targets; and SDG 17 (Partnerships for the goals), where it is linked to 47% of targets. No primary direct contribution was found between engineering geology and SDG 5 (Gender equality), SDG 10 (Reduced inequalities), SDG 16 (Peace, justice and strong institutions) and SDG 17 (Partnerships for the goals), although in all cases secondary direct contributions were identified.

The findings of the analysis identified opportunities for engineering geologists to strengthen their contribution to all 17 of the UN SDGs. Engineering geologists have the greatest opportunity to strengthen their contribution to: SDG 17 (Partnerships for the goals), where seven opportunity targets were identified; SDG 12 (Responsible consumption and production) and SDG 16 (Peace, justice and strong institutions), where six opportunity targets were identified for both cases; and SDG 7 (Affordable and clean energy), where five opportunity targets were identified.

Discussion

The assessment highlights a number of key impact areas where engineering geologists already contribute to sustainable development. Three key impact areas have been derived from primary direct contributions: construction and infrastructure development; disaster risk reduction; and environmental protection and delivery of nature-based solutions/environmentally sensitive design. Two further key impact areas have been derived from secondary direct contributions: building an equitable and effective community; and collaboration and strong partnerships (including engaging in policy-level processes). A summary of how engineering geologists already contribute to these key impact areas is provided below, as well as a discussion on how they can enhance their impact by strengthening their contributions.

Figure 3 summarizes the broad range of engineering geological activities identified in the assessment derived from the three primary impact areas, noting that many activities contribute to more than one focus area. It expands upon the *Geoscience for the Future* poster published by the Geological Society of London in 2020, identifying the UN SDGs that relate to each activity.

The role of engineering geology in sustainable construction and infrastructure development

The purpose of infrastructure is to provide fundamental societal needs such as transportation, energy supply, water and sanitation,

Table 2. *Summary of SDG targets dependent on engineering geology knowledge, skills and activities: the percentage of total number of SDG targets dependent on engineering geology knowledge, skills and activities are shown in parentheses*

UN Sustainable Development Goals (SDGs)	Total targets	Direct contribution, primary	Direct contribution, secondary	Indirect contribution	Total of targets dependent	Independent	Opportunity to strengthen contribution	Prevailing dependence
SDG 1 (No poverty): 1.1, eradicate extreme poverty (IC); 1.2, reduce poverty by at least half (IC); 1.4, equal rights to economic resources (IC); 1.5, build resilience of poor and vulnerable to shocks and disasters (PDC);1b, create sound policy and frameworks to support poverty eradication (IC)	7	1 (14%)	0 (0%)	4 (57%)	5 (71%)	2 (29%)	1 (14%)	Indirect
SDG 2 (Zero hunger): 2.1, end hunger (IC); 2.2, end all forms of malnutrition (IC); 2.3, double agricultural productivity (IC); 2.4, ensure sustainable food production (PDC); 2.5, maintain genetic diversity of seeds, plants and animals (IC)	8	2 (25%)	0 (0%)	4 (50%)	6 (75%)	2 (25%)	1 (13%)	Indirect
SDG 3 (Good health and well-being): 3.1, reduce maternal mortality (IC); 3.2, end preventable deaths of newborns and children under 5 (IC); 3.3, end epidemics of AIDS, TB, malaria and tropical diseases (PDC); 3.4, reduce premature mortality by a third from non-communicable diseases (PDC); 3.6, halve deaths and injuries from road accidents (PDC); 3.9, reduce death and illness from chemicals, and soil, water and air pollution and contamination (PDC); 3.d, strengthen capacity for early warning, risk reduction and management of health risks (PDC)	13	5 (38%)	0 (0%)	2 (15%)	7 (54%)	6 (46%)	1 (8%)	Direct, primary
SDG 4 (Quality education): 4.1, ensure girls and boys complete primary and secondary education (IC); 4.4, increase number of youths and adults with relevant skills for employment (SDC); 4.5, eliminate gender disparity in education and training (SDC); 4.7, ensure learners acquire knowledge and skills for sustainable development (SDC); 4.a, build and upgrade educational facilities that are child, disability and gender sensitive (PDC); 4.b, expand number of scholarships available for developing countries (SDC)	10	1 (10%)	4 (40%)	1 (10%)	6 (60%)	4 (40%)	4 (40%)	Direct, secondary
SDG 5 (Gender equality): 5.1, end discrimination against women and girls (SDC); 5.2, eliminate violence against women and girls (SDC); 5.3, recognize and value unpaid care and domestic work (SDC); 5.5, ensure women's participation and equal opportunities for leadership (SDC); 5.c, adopt and enforce policies and legislation for gender equality (IC)	9	0 (0%)	4 (44%)	1 (11%)	5 (56%)	4 (44%)	4 (44%)	Independent
SDG 6 (Clean water and sanitation): 6.1, safe and affordable drinking water for all (PDC); 6.2, adequate and equitable sanitation and hygiene for all (PDC); 6.3, improve water quality (PDC); 6.4, increase water-use efficiency (PDC); 6.6, protect and restore water-related ecosystems (PDC); 6.b, support local communities improve water and sanitation management (IC)	8	5 (63%)	0 (0%)	1 (13%)	6 (75%)	2 (25%)	4 (50%)	Direct, primary
SDG 7 (Affordable and clean energy): 7.1, access to affordable, reliable and modern energy services (PDC); 7.2, increase share of renewable energy (PDC); 7.3, double rate of improvement in energy efficiency (PDC); 7.a, enhance international cooperation for clean energy technology and research (PDC); 7.b, expand and upgrade infrastructure and technology for modern energy services (IC)	5	4 (80%)	0 (0%)	1 (20%)	5 (100%)	0 (0%)	5 (100%)	Direct, primary
SDG 8 (Decent work and economic growth): 8.1, sustain per capita economic growth (IC); 8.2, higher levels of economic productivity (IC); 8.4, improve resource efficiency in consumption and production (PDC); 8.5, full and productive employment (SDC); 8.6, reduce youths not in employment, training or education (SDC); 8.7, eradicate forced labour, modern slavery, human trafficking and child labour (SDC); 8.8, protect labour rights (SDC); 8.9, policies to promote sustainable tourism (IC); 8.10, strengthen domestic financial institutions (IC)	12	1 (8%)	4 (33%)	4 (33%)	9 (75%)	3 (25%)	3 (25%)	Direct, secondary

(continued)

Table 2. *(Continued)*

UN Sustainable Development Goals (SDGs)	Total targets	Direct contribution, primary	Direct contribution, secondary	Indirect contribution	Total of targets dependent	Independent	Opportunity to strengthen contribution	Prevailing dependence
SDG 9 (Industry, innovation and infrastructure): 9.1, sustainable and resilient infrastructure (PDC); 9.2, inclusive and sustainable industrialization (IC); 9.4, upgrade and retrofit infrastructure and industry to enhance sustainability (PDC); 9.5, enhance research and technology capabilities of industrial sectors (SDC); 9.a, enhance financial and technical support for sustainable and resilient infrastructure in least developed countries (SDC); 9.b, support domestic technology development, research and innovation (IC); 9.c, increase access to information and communications technology (ICT) (PDC)	8	3 (38%)	2 (25%)	2 (25%)	7 (88%)	1 (13%)	1 (13%)	Direct, primary
SDG 10 (Reduced inequalities): 10.3, ensure equal opportunities and reduce inequalities of outcome (SDC); 10.6, enhanced representation and voice for developing countries in decision-making (SDC)	10	0 (0%)	2 (20%)	0 (0%)	2 (20%)	8 (80%)	2 (20%)	Independent
SDG 11 (Sustainable cities and communities): 11.1, adequate, safe and affordable housing and services (PDC); 11.2, access to safe and affordable transport systems (PDC); 11.3, inclusive and sustainable urbanization (PDC); 11.4, protect and safeguard cultural and natural heritage (PDC); 11.5, reduce deaths, people effected and economic loss from disasters (PDC); 11.6, reduce environmental impact of cities (PDC); 11.b, increase number of cities and settlements adopting and implementing plans for DRR (PDC); 11.c, support least developed countries in building sustainable and resilient buildings from local materials (SDC)	10	7 (70%)	1 (10%)	0 (0%)	8 (80%)	2 (20%)	2 (20%)	Direct, primary
SDG 12 (Responsible consumption and production): 12.1, implement the 10 Year Framework of Programmes on Sustainable Consumption and Production Patterns (PDC); 12.2, sustainable management and efficient use of natural resources (PDC); 12.3, halve global food waste, and reduce loss from production and supply chains (IC); 12.4, environmentally sound management of chemicals and all wastes throughout their life cycle (PDC); 12.5, reduce waste generation through prevention, reduction, recycling and reuse (PDC); 12.6, encourage companies to adopt sustainable practices and integrate sustainability reporting (SDC); 12.7, promote sustainable public procurement practices (SDC); 12.8, ensure people have relevant information for sustainable development and lifestyles (SDC); 12.a, support developing countries to move towards sustainable patterns of consumption and production (SDC)	11	4 (36%)	4 (36%)	1 (9%)	9 (82%)	2 (18%)	6 (55%)	Direct, primary
SDG 13 (Climate action): 13.1, strengthen resilience to climate-related hazards and natural disasters (PDC); 13.2, integrate climate change measures into national policies, strategies and planning (PDC); 13.3, improve capacity on climate change mitigation, adaptation, impact reduction and early warning (SDC); 3.b, raise capacity for effective climate-change-related planning and management in least developed countries (PDC)	5	3 (60%)	1 (20%)	0 (0%)	4 (80%)	1 (20%)	1 (20%)	Direct, primary
SDG 14 (Life below water): 14.1, by 2025, prevent and reduce marine pollution (IC); 14.2, sustainably manage and protect marine and coastal ecosystems (PDC); 14.5, conserve at least 10% of coastal and marine areas (IC); 14.a, increase scientific knowledge, develop research capacity and transfer technology to improve ocean health (SDC)	10	1 (10%)	1 (10%)	2 (20%)	4 (40%)	6 (60%)	2 (20%)	Independent

SDG 15 (Life on land): 15.1, ensure conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems (PDC); 15.2, promote implementation of sustainable management of forests (PDC); 15.3, combat desertification (PDC); 15.4, ensure conservation of mountain ecosystems (PDC); 15.5, reduce degradation of natural habitats, halt loss of biodiversity and, prevent extinction of threatened species (PDC); 15.8, prevent introduction and reduce impact of invasive alien species (PDC); 15.9, integrate ecosystem and biodiversity values into planning, development processes, poverty reduction strategies and accounts (PDC)	12	7 (58%)	0 (0%)	0 (0%)	7 (58%)	5 (42%)	4 (33%)	Direct, primary
SDG 16 (Peace, justice and strong institutions): 16.1, reduce all forms of violence and related death rates (SDC); 16.2, end abuse, exploitation, trafficking, violence and torture of children (SDC); 16.5, reduce corruption and bribery (SDC); 16.6, develop effective, accountable and transparent institutions (SDC); 16.7, ensure responsive, inclusive, participatory and representative decision-making (SDC); 16.8, strengthen participation of developing countries in governance of global institutions (SDC); 16.10, ensure public access to information and protect fundamental freedoms (SDC); 16.b, promote and enforce non-discriminatory laws and policies for sustainable development (SDC)	12	0 (0%)	8 (67%)	0 (0%)	7 (58%)	5 (42%)	5 (42%)	Direct, secondary
SDG 17 (Partnerships for the goals): 17.2, developed countries to implement ODA commitments (SDC); 17.6, enhance north–south, south–south and triangular cooperation on science, technology, innovation knowledge-sharing (SDC); 17.7, promote development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries (SDC); 17.8, science, technology and innovation capacity-building mechanism for least developed countries (IC); 17.9, enhance support for effective and targeted capacity-building in developing countries to support SDGs (SDC); 17.11, increase the exports of developing countries (IC); 17.14, enhance policy coherence for sustainable development (SDC); 17.16, enhance the Global Partnership for Sustainable Development (SDC); 17.17, encourage and promote effective public, public–private and civil society partnerships (SDC)	19	0 (0%)	7 (37%)	2 (11%)	9 (47%)	10 (53%)	7 (37%)	Independent
Total	169	44 (26%)	38 (22%)	25 (15%)	107 (63%)	62 (37%)	54 (32%)	

PDC, primary direct contribution; SDC, secondary direct contribution; IC, indirect contribution. SDG target descriptions are abridged, the full target descriptions are provided in the Supplementary material.

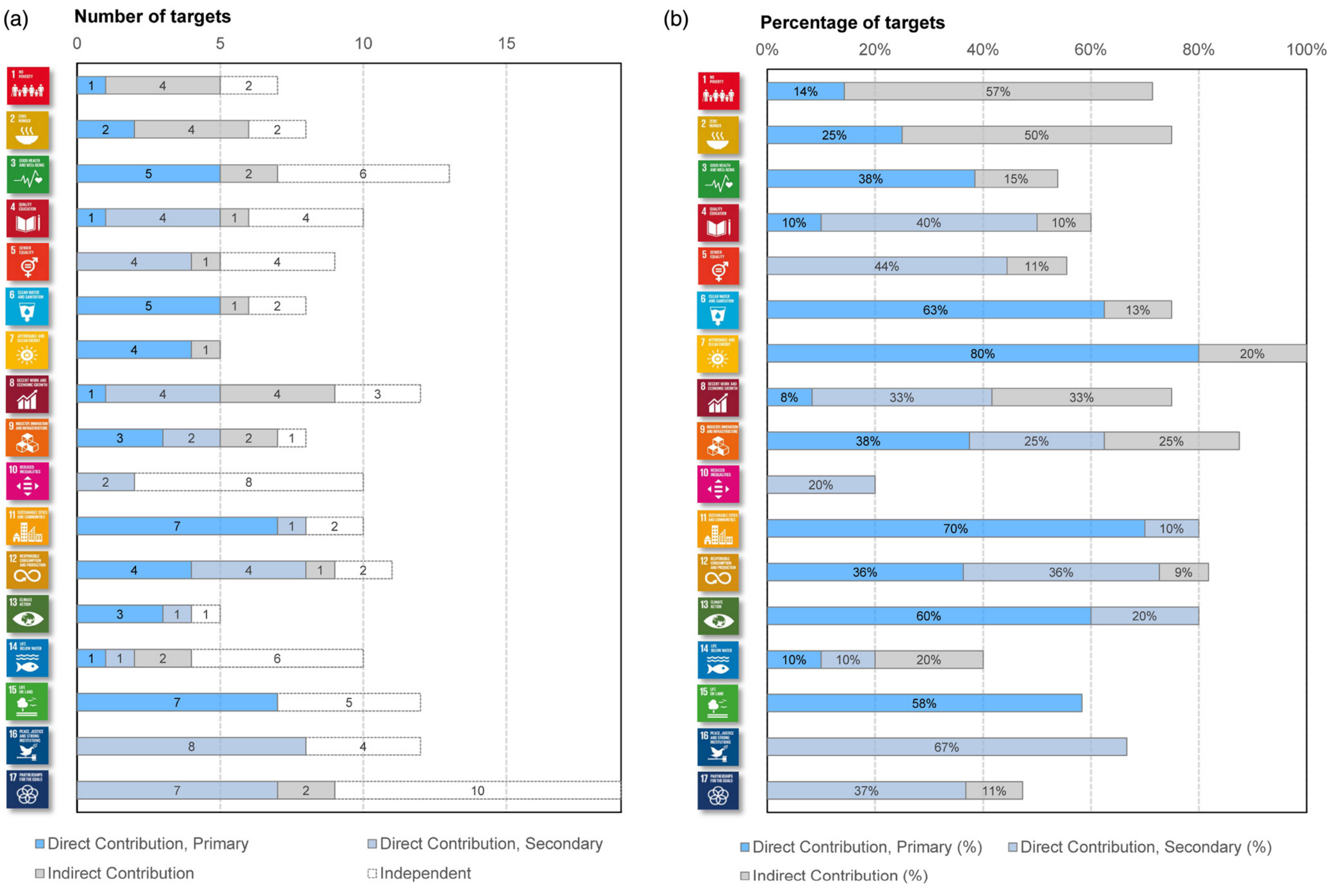

Fig. 2. SDG targets that are directly or indirectly dependent on engineering geology knowledge, skills and activities by number of targets (**a**) and percentage of total number of targets (**b**).

waste management, food supply, shelter, education, and healthcare etc. The broader *outcomes* infrastructure systems facilitate go beyond these basic functions, meaning that infrastructure development also plays a key role in addressing many of the socio-economic and environmental challenges covered by the SDGs (United Nations 2015; *The Economist* Intelligence Unit 2019; Institution of Civil Engineers 2020). For example, improved water and sanitation facilities (SDG 6) at schools will allow girls to stay in education when they are menstruating, supporting gender equality (SDG 5). However, current investment in infrastructure globally is insufficient to maintain existing service levels in line with projected social and economic growth (Dobbs *et al.* 2013; Woetzel *et al.* 2016)

Thacker *et al.* (2018) identified that infrastructure systems contribute to between 72 and 81% of the SDG targets across all 17 goals. For these targets related to infrastructure development, the mapping exercise presented in this paper identified primary direct dependencies for 80 (47%) targets, as well as secondary direct dependencies for 25 (15%) targets and indirect dependencies for 24 (14%) targets, as related to engineering geology knowledge, skills and activities; key examples of these contributions include:

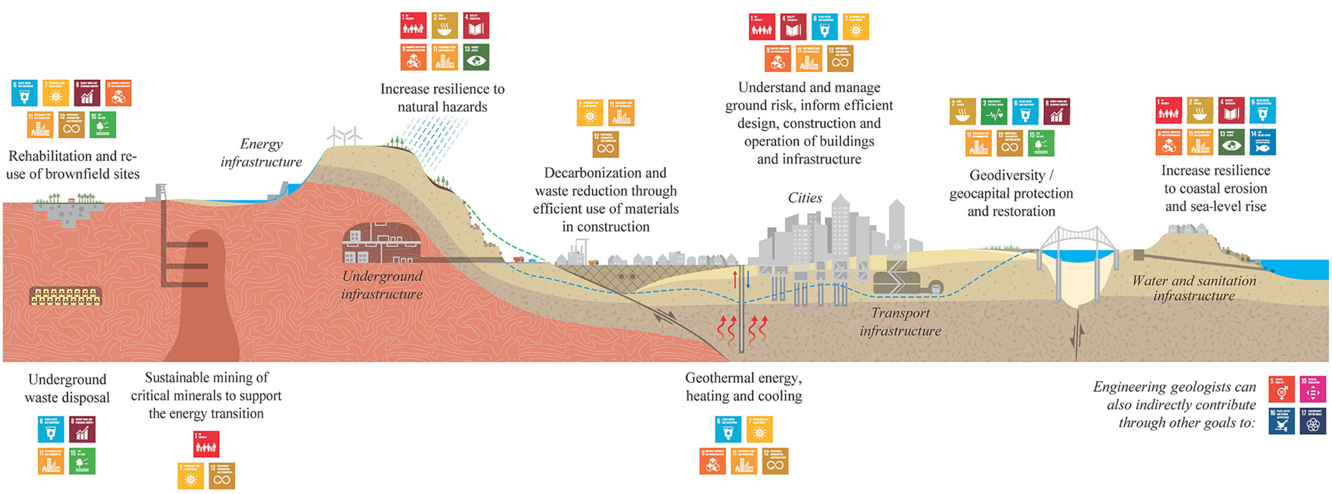

Fig. 3. Conceptual ground model showing the contributions of engineering geology to sustainable development.

(1) developing ground models, characterizing geological materials, assessing geohazard risk, and informing the planning, efficient design, construction, operation and maintenance of sustainable and resilient infrastructure, including waste disposal, energy, mining, water and sanitation, transportation and cities, as illustrated in Figure 3 (targets 1.4, 2.1, 2.3, 2.5, 3.1, 3.2, 3.3, 3.6, 4.1, 6.1, 6.2, 6.3, 6.4, 7.1, 7.2, 8.1, 8.2, 8.9, 8.10, 9.1, 9.2, 9.4, 9.a, 9.c, 11.1, 11.2, 11.3, 12.3, 16.1 and 17.8);

(2) enhancing construction productivity by substantially reducing cost and time overruns due to unforeseen ground conditions (targets 8.1, 8.2, 8.4, 9.1, 9.4 and 11.3); and

(3) assessing the re-use opportunities of excavation spoil, and developing material treatment and remediation strategies that minimize the import of materials and construction waste (targets 2.2, 2.3, 12.1, 12.2, 12.5 and 14.1).

Despite their already significant contribution to infrastructure development, engineering geologists can produce a greater impact by enhancing the sustainable outcomes of the infrastructure projects they support.

The current under-investment in infrastructure globally, known as the 'infrastructure gap', threatens to undermine projected social and economic growth. Productivity must be improved within the construction sector to help combat this (Dobbs *et al.* 2013). Ground failure and unforeseen ground conditions are estimated to be, on average, responsible for significant delays in at least 20% of construction programmes and cost overruns of at least 10% (Littlejohn *et al.* 1994; Gould 1995; Fookes 1997; Brandl 2004; Chapman and Marcetteau 2004; *The Economist* 2005; van Staveren 2006; Chapman 2012). As highlighted by Baynes *et al.* (2020), a good engineering geological model is powerful in managing ground risk. Understanding and managing the variability of the ground, including any contamination, is critical for the development of a design that can be constructed safely yet efficiently, minimizing the use of materials, creation of waste and environmental impacts of construction, including carbon emissions and the spread of soil and groundwater contamination. As such, engineering geology has a key role in improving productivity within construction. Engineering geologists need to do more to communicate the value that they bring to the planning, design and construction processes in characterizing ground risks and anticipating adverse ground conditions.

Figure 4 illustrates the life cycle of an infrastructure project, highlighting when the typical contributions of engineering geologists occur at each project stage. As highlighted by Pantelidou *et al.* (2012), the biggest opportunities to apply sustainable solutions during project delivery are in the earlier planning stages, diminishing as planning and design progresses, and becoming quite limited during construction. Conversely, the cost of affecting design changes increases over time. Mansell *et al.* (2019*a*, *b*) consider the broader view of the infrastructure development life cycle and how making better choices about which project to execute (i.e. 'doing the right projects'), with a focus on project outcomes, is a more effective way to achieve greater impact than through project delivery (i.e. 'doing projects right') (Fig. 5). The typical contribution of engineering geologists is during project delivery in the latter stages of project planning and the early stages of design. At the time of their involvement, which project to execute and the strategic definition of the project has already been established. This provides an opportunity to broaden their engagement with these earlier life-cycle stages and to influence project definition and strategic decision-making, with a focus on maximizing sustainable outcomes.

While the greatest impact can be achieved in these early stages, engineering geological modelling at all stages of the project life cycle can also be improved by greater investment in high-quality ground investigation and wider sharing of existing geological and geotechnical data through national and regional databases (e.g. BRO in The Netherlands: von der Tann *et al.* 2018; and Dig to Share in the UK: I3P 2021; (COST) Action (SUB-URBAN: TU1206) in the EU: Fordyce and Campbell 2019). There is also an opportunity for engineering geologists to be engaged more during construction operations with, for example, construction managers and resident engineers to observe and advise on encountered ground conditions; developing live geological ground models that are updated whenever new information and data become available, and that are properly integrated with other construction information, such as building information modelling (BIM) and digital twin (e.g. Kessler *et al.* 2015; Terrington *et al.* 2019; Turner *et al.* 2021).

The role of engineering geology in disaster risk reduction

It is widely recognized that disaster risk reduction is a key element of sustainable development (UNDP 2013). Disasters threaten development progress, and disproportionately affect the poor and marginalized (Pelling *et al.* 2004) Addressing socio-economic sustainable development challenges can increase individual, community, institutional and infrastructural resilience through a reduction in exposure and/or vulnerability to hazards (UNDP 2004). As such, resilience to natural hazards is embedded into the UN SDGs.

A UN analysis identified 25 targets, across 10 of the UN SDGs, that relate to disaster risk reduction (UNDRR 2015*b*). For those targets related to disaster risk reduction, the mapping exercise presented in this paper identified primary direct dependencies for 20 (12%) targets, as well as secondary direct dependencies for three (2%) targets, as related to engineering geology knowledge, skills and activities. Key examples of these contributions include:

(1) carrying out natural hazard assessments to determine the risk to communities and infrastructure, informing planning, design, construction, asset management and disaster recovery strategies, such as landslides and rockfalls, as illustrated in Figure 3 (targets 1.5, 3.d, 11.2, 11.5, 11.b, 13.1, 13.2 and 16.1);

(2) assessing the effects of climate change on geohazards, and contributing to strategies that enable effective planning and design for future climate scenarios such as sea-level rise and increased coastal erosion, as illustrated in Figure 3 (targets 1.5, 13.2 and 13.b); and

(3) identifying hazardous chemicals in water and soil, and harmful levels of geogenic materials (e.g. radon gas), and providing advice on reducing water and soil pollution and contamination risks through remediation to enable rehabilitation and reuse of contaminated sites, as illustrated in Figure 3 (targets 3.4, 3.9, 6.1 and 6.3).

Despite the already strong contribution to disaster risk reduction, there are further opportunities for engineering geologists to contribute better to the planning and development of sustainable and resilient communities.

In addition to the 25 targets identified by UNDRR (2015*b*), progress towards other targets can help to strengthen scientific capacity and institutional capability in disaster risk reduction. The Sendai Framework for Disaster Risk Reduction 2015–30 (UNDRR 2015*a*) sets out four 'Priorities for action'. 'Priority 1: understanding disaster risk' includes understanding hazard characteristics and the environment for risk assessment, prevention, mitigation, preparedness and response. There is an opportunity for further research and innovation in relation to the impacts of climate change on geohazard: for example, modelling the effect of projected increase in rainfall intensity on landslide risk; and the impact of projected sea-level rise on coastal erosion. The impacts of climate change are not yet being routinely considered during planning, design and geohazard risk assessment. More can also be done in

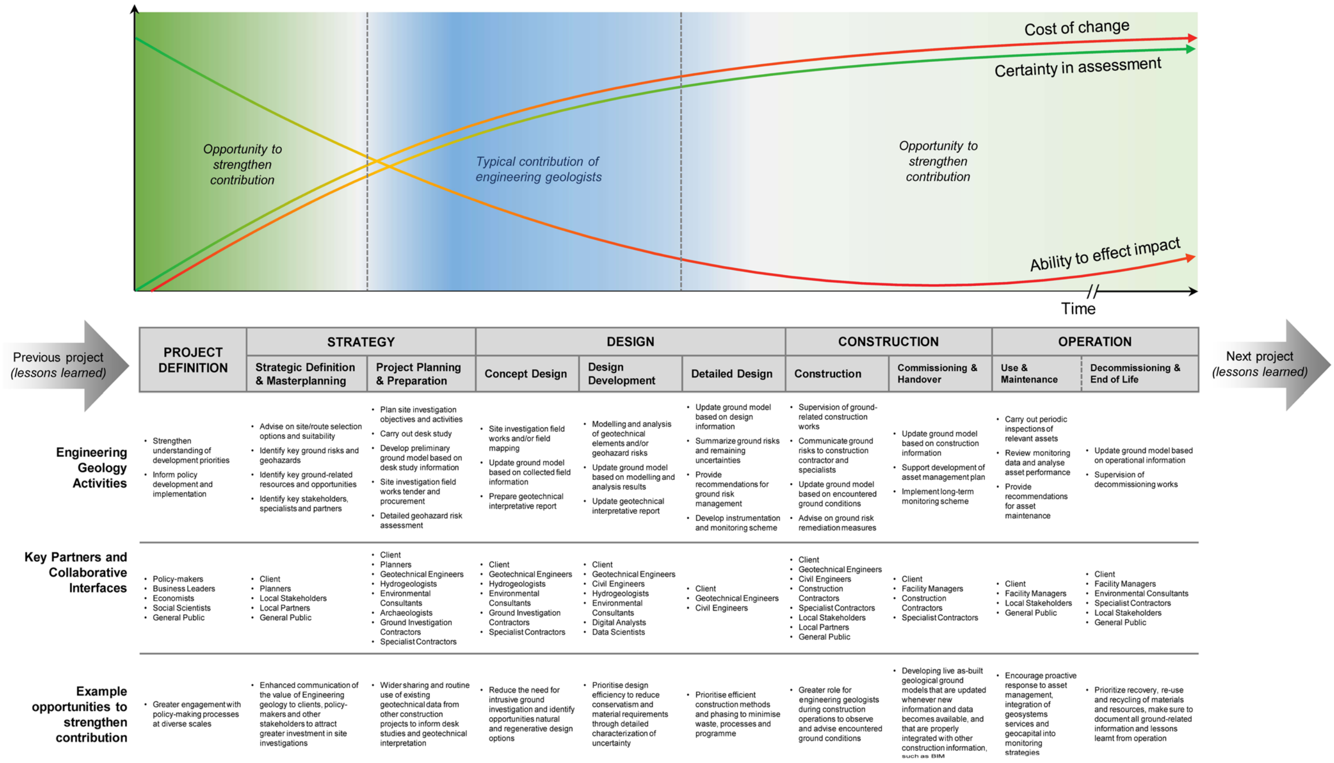

Fig. 4. Conceptual diagram showing the ability to affect the impact towards and the cost of change sustainable development across the project life cycle. The diagram also highlights the key activities of engineering geologists, as well the key partners and collaborative interfaces – adapted from the MacLeamy curve (MacLeamy 2004) and figure 4 of PAS 2080:2016 (BSI 2016).

terms of sharing knowledge and understanding of geohazard risk assessment globally, working with social scientists to understand local context, upskilling local scientists and partnering with local institutions in vulnerable communities to improve their resilience to geohazards.

Given the complex challenges posed by disasters, and the need for a holistic approach to disaster risk reduction and management, Gill *et al.* (2021) recommend shifting from characterizing multiple single hazards to a multi-hazard approach. This considers the interrelationships between hazards and their cascading, consecutive or concurrent impacts on natural, built and social systems. An integrated approach is key to ensuring actions taken to reduce vulnerability to one hazard do not inadvertently increase vulnerability to others. In this context, strengthening the contribution of engineering geologists to deliver the UN SDGs means breaking down professional and disciplinary silos, and facilitating closer engagement with other natural hazard scientists (e.g. hydrologists, meteorologists and public health professionals) and social scientists. Approaches to support this include the setting up cross-agency hazard partnerships (e.g. the UK's Natural Hazards Partnership),

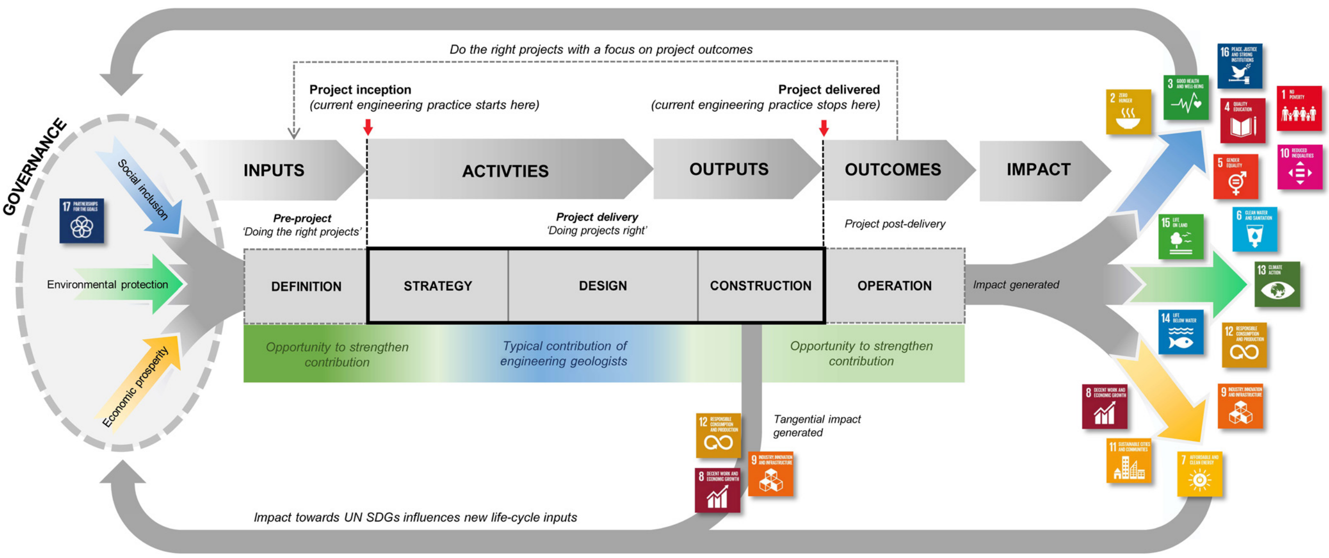

Fig. 5. Conceptual diagram illustrating how impact towards the UN SDGs is generated over the whole life cycle of a project including pre-project delivery, project delivery and post-project delivery – adapted from Adams (2017) and Mansell *et al.* (2019*a*, *b*).

and ensuring that the structure of scientific unions allows for cross-disciplinary conversations and research development (e.g. the European Geosciences Union have a 'multi-hazard' subdivision).

The role of engineering geology in environmental protection

Environmental protection and enhancement are integrated within all 17 UN SDGs, reflecting the extent to which social and economic development is dependent on, as well as having potential to cause harm to, the environment. Climate change associated with increasing atmospheric greenhouse gas concentrations is considered the single biggest threat to social and economic development, and the environment. Implementation of the 2015 Paris Agreement of the UN Framework Convention on Climate Change is essential in achieving the UN SDGs. The overall aim of the Paris Agreement is to limit global warming to no more than 1.5°C by transitioning to net-zero carbon emissions by 2050. The urgent need for rapid, large-scale and sustained reduction in emissions is highlighted by the IPPC's Climate Change 2021 Report (IPCC 2021). Planning, design and construction of the built environment must consider the competing needs of social development and environmental protection, including carbon emissions and sequestration.

The UN Environment Programme (UNEP) identified 85 environment-related SDG targets (UNEP 2019). For those targets related to environmental protection, the mapping exercise presented in this paper identified primary direct dependencies for 34 (20%) targets, as well as secondary direct dependencies for 13 (8%) targets and indirect dependencies for eight (5%) targets, as related to engineering geology knowledge, skills and activities. Key examples of these contributions include:

(1) supporting the feasibility, planning, design, construction, operation and maintenance of infrastructure for waste treatment and disposal, carbon capture and sequestration, and clean energy generation, transmission and storage such as geothermal, wind, hydropower, energy storage, as illustrated in Figure 3 (targets 1.5, 6.1, 6.2, 6.4, 7.1, 7.2, 7.3, 9.4 and 11.5);

(2) minimizing the surface impact of the built environment through subsurface characterization, and supporting the development of foundations, engineered slopes and subsurface infrastructure, as illustrated in Figure 3 (targets 9.1, 11.2 and 11.3);

(3) maximizing the efficient use of natural resources, minimizing waste and embodied carbon in construction through efficient design by characterizing material properties, and identifying and implementing material re-use and improvement strategies, as illustrated in Figure 3 (targets 8.4, 12.1, 12.2 and 12.5);

(4) working with hydrogeologists and ecologists to safeguard biotic and abiotic systems by identifying contamination sources, pathways and receptors, and developing, implementing and monitoring remediation strategies for protecting or enhancing air, soil and water quality (geodiversity and geocapital), as illustrated in Figure 3 (targets 2.4, 3.9, 6.1, 6.6, 8.4, 11.4, 12.2, 12.4, 12.5 and 15.9); and

(5) working with hydrogeologists, hydrologists, drainage engineers, urban designers and ecologists to deliver nature-based, nature-considerate and regenerative engineering solutions, such as quarry and mine rehabilitation and re-use, as identified in Figure 3, green slopes, and sustainable urban drainage systems (SuDS) (targets 6.4, 6.6, 14.2 and 15.9).

Despite the already strong contribution to environmental protection, there are further opportunities for engineering geologists to enhance their contribution.

The day-to-day activities of engineering geologists and the operation of the organizations that they work for are a source of carbon emissions and waste. Engineering geologists should pursue the adoption of new technologies and other options for reducing emissions, waste and other pollution within their operations. However, engineering organizations can have an even greater influence on environmental protection through the projects that they work on by considering whole of life carbon, circularity and waste minimization during design. Engineering geologists already contribute to the reduction of embodied carbon by helping designers to understand the ground but can strengthen their contribution by working with engineers and materials experts to drive the use of less carbon-intensive materials in construction: for example, alternatives to cement and lime for earthworks treatment (e.g. microbial-induced calcite precipitation application (MICP): Osinubi *et al.* 2019). An even greater impact can be achieved by advocating for schemes that minimize user and operational carbon, which typically have greater significance in terms of whole of life carbon than embodied carbon. For example, engineering geologists would have an important role to play in determining the feasibility of a water supply tunnel through mountainous terrain to optimize gravitational feed and avoid significant operational carbon associated with pumping up and over a mountain. In addition to reducing carbon as part of the planning and design process, they can also contribute to the development and inclusion of initiatives to remove greenhouse gases from the atmosphere, such as enhanced mineral weathering within their projects.

Further to the significant contribution that engineering geologists make to support the clean energy transition, including directly to the development of sustainable shallow subsurface heat-recovery schemes (Brabham *et al.* 2019; Patton *et al.* 2020; Monaghan *et al.* 2021), wider upskilling of the workforce will be required within specialist areas such as offshore environments to support an increasing volume of offshore wind-farm projects globally. A greater knowledge of deep geology, increased application of rock mechanics and better understanding of hydromechanical–chemical coupling is also needed to support the development of new underground carbon capture and storage (CCS), energy storage, and radioactive-waste-disposal technologies (Evans *et al.* 2009). Engineering geology will also have an important role to play in the development of mining infrastructure for the extraction of rare earth elements and other minerals that are critical for the transition to renewable energy and the electrification of transport systems, as illustrated in Figure 3.

Natural capital is defined as the world's stocks of natural assets from which humans derive a wide range of services (often called ecosystem services) that make human life possible. This includes rocks, soil, air, water and all living things. Geodiversity, which refers to the variation in the Earth's abiotic processes and features, has a strong influence on biodiversity (Fox *et al.* 2020). Engineering geologists can influence environmental planning by promoting the role of geodiversity alongside biodiversity in providing ecosystem services (Schrodt *et al.* 2019). New initiatives for considering net biodiversity gain during the planning process, such as those being integrated into development projects in the UK (DEFRA 2019), present an opportunity for engineering geologists to work with ecologists to integrate geocapital in natural capital accounting frameworks and to contribute to strategies to achieve a net gain in natural capital through the project life cycle (Gordon and Barron 2013; Van Ree and Beukering 2016; Fox *et al.* 2020).

The role of engineering geology in building an equitable and effective community

While the UN SDGs are relevant to all contexts, people and segments of society, they have a focus on 'leaving no one behind'. Agenda 2030 (United Nations 2015) highlights the specific challenges faced by the world's least developed countries, landlocked developing countries and small island developing states (SIDS), as well as countries where there is, or has recently been, armed conflict. A repeated theme of the UN SDGs is the need to provide extra support to these regions, which include some of the world's most vulnerable communities, to ensure that they have an equitable share in a sustainable and prosperous future. The principle of 'leaving no one behind' goes further than this to include tackling inequalities and barriers to inclusion of every type, and at every scale and level.

For those targets related to building an equitable and effective community, the mapping exercise presented in this paper identified primary direct dependencies for 10 (6%) targets, as well as secondary direct dependencies for 21 (12%) targets and indirect dependencies for nine (5%) targets, as related to engineering geology knowledge, skills and activities. Key examples of these contributions include:

(1) increased access to engineering geology by under-represented groups in all national contexts including regions identified in Agenda 2030 as needing extra support; this includes providing sponsorship or scholarships to increase access to postgraduate training in contexts where resources are limited, ensuring a strengthened supply of engineering geologists (targets 1.2, 4.4, 4.5, 4.7, 4.b, 10.6, 13.3, 13.b and 17.9);

(2) tackling inequalities and abuses in the sector, and developing organizational policies and processes to tackle discrimination against women and minority groups (targets 5.1, 5.2, 5.4, 5.5, 10.3, 16.2 and 16.5); and

(3) strengthening institutions, and ensuring inclusive and transparent decision-making; ensuring representation and voices of engineering geologists from developing countries in international organizations, such as scientific unions and professional societies (targets 5.5 10.6, 16.5, 16.6, 16.7, 16.8, 17.14 and 17.16).

Although engineering geologists already contribute to building an equitable and effective community, there are further opportunities to strengthen their contribution within educational contexts, individual organizations, and both national and international professional communities.

How engineering geology activities are conducted, and institutions operate, can directly affect the extent to which projects achieve a long-lasting, positive impact. Institutions with inclusive decision-making can help to tackle inequalities, and ensure safe and secure work environments. Increasing access to engineering geology training for marginalized groups can help to build organizations with the collective intellect, creativity and range of perspectives required to innovate and address pressing scientific and societal challenges.

To help build a more equitable engineering geology community, with effective and transparent institutions, geoethics should be embedded into the training of engineering geologists. Geoethics is an emerging field, exploring the values that underpin appropriate behaviours and practices, and the social role and responsibility of geoscientists in conducting their activities (Di Capua and Peppoloni 2019; Di Capua *et al.* 2021). By including geoethics in their training, it equips engineering geologists with the skills and tools they need to examine critically *how* they work, and whether this will support or hinder efforts to tackle inequalities. Training in geoethics should be supplemented by existing institutional and organizational ethical frameworks: for example, the Geological Society of London's Code of Conduct.

Another action is to ensure a greater emphasis on commitment to diversity, equality and inclusion in the assessment criteria for chartership and other professional certifications, while also creating or supporting forums for the sharing of good practices between institutions, sectors and nations. As professionals, engineering geologists should take personal and collective responsibility for driving equity within their profession and beyond.

The role of engineering geology in delivering sustainable development through collaborative and strong partnerships

It is widely recognized that success in achieving the UN SDGs will be underpinned by the principles of SDG 17 (Partnerships for the goals). Collaborations to address sustainability challenges need to bring together those in academia, industry, the public sector and civil society organizations. Each brings different perspectives and resources to achieve a greater development impact than any individual sector could achieve alone (Stibbe and Prescott 2016). For example, by working with industry, academics can ensure research questions are aligned to societal needs. Industry can also support the translation of knowledge and innovation into practice, establishing clear impact pathways for academic work. In return, working with academia brings access to data, knowledge and expertise that can inform industry-relevant tools and approaches. For example, the UK Natural Environment Research Council's Environmental Risks to Infrastructure Innovation Programme (ERIIP) brought together academia and the infrastructure sector to facilitate access to knowledge of environmental risks (NERC 2021).

For those targets related to collaborative and strong partnerships, the mapping exercise presented in this paper identified primary direct dependencies for eight (5%) targets, as well as secondary direct dependencies for 16 (9%) targets and indirect dependencies for five (3%) targets, as related to engineering geology knowledge, skills and activities. Key examples of these contributions include:

(1) contributing to international research and multi-sector partnerships to co-develop solutions, and to share knowledge, data and technology for waste treatment, waste disposal, generating and storing clean energy, nature-based solutions, and sustainable consumption (targets 6.a, 7.3, 7.a, 9.5, 9.a, 12a, 13.3, 13.b, 14.2, 14a, 17.6, 17.7, 17.16 and 17.17);

(2) engagement in local, national, regional and global policy processes to ensure understanding of the subsurface (risks and opportunities) is embedded into planning policies and strategies – supporting their alignment with parallel policies on environmental protection, resource use and management, and disaster and emergency risk reduction and management (targets 1.b, 10.3, 12.6, 12.7, 12.8, 16.1, 16.6, 16.7, 16.8, 16.10, 16b and 17.7); and

(3) building capacity and facilitating knowledge and technology transfer in engineering geology, through global partnerships, and thus supporting developing countries to address SDGs (targets 3.d, 6.b, 9.5, 9.b, 10.6 11.c, 12.a, 13.b, 17.7, 17.9 and 17.16).

Although engineering geologists are already collaborating and building strong partnerships, there are further opportunities to strengthen this engagement.

As illustrated in Figure 4, engineering geologists engaged in infrastructure (and other) projects regularly collaborate with engineers, architects, urban designers, transport planners, ecologists, heritage specialists, social scientists, environmental planners, sustainability consultants and economists over the project life cycle. They also work with stakeholders across multiple sectors, including transport infrastructure, buildings, energy, mining, waste, water, health and education, both within the developing and the developed world context, and in public and privately owned organizations, as well as non-governmental organizations (NGOs). To maximize their impact, engineering geologists should engage with stakeholders higher up the value chain that have the most influence over project definition and strategic decision-making, such as clients, planners, policy-makers and business leaders. They should also explore new opportunities to collaborate or partner with academia, NGOs, private firms, start-ups, academic institutions or innovation labs. International multi-stakeholder partnerships must support the levelling up of developing countries and underprivileged communities through dissemination of knowledge, expertise and technology, and via effective capacity building.

Engagement of engineering geologists in policy processes can both strengthen *understanding* of development priorities and increase opportunities to *inform* policy development and implementation to improve projects. Participation in international (including global) policy mechanisms can encourage dialogue on the importance of the subsurface and interactions between the natural and built environments and society, shaping outputs that feed through into the policies, strategies and actions taken by regional bodies, and national and local governments. Participation in national-level policy processes can help to shape the development and implementation of policy. Examples of opportunities to engage with policy-level initiatives at these different scales include the Global Technology Facilitation Mechanism (global) and the UK Engineering in Policy Network (national), which both facilitate collaboration and partnerships through the sharing of information, experiences, best practices and policy advice. They provide opportunities for engineering geologists (and other geoscientists) to contribute to policy processes through science-for-development forums, joining expert groups and responding to calls-for-evidence to inform flagship reports (such as the quadrennial *Global Sustainable Development Report*) (InterAcademy Partnership 2019).

Organizations with members or followers from the engineering geology community are active in this space. For example, the UK-based NGO Geology for Global Development participate in UN-level forums and respond to calls for evidence. In 2021, they secured observer status to the UN Framework Convention on Climate Change, and embedded the importance of geodiversity in a UN Scientific and Technological Community Major Group position paper prepared for the 2021 UN High-Level Political Forum on Sustainable Development (STC MG 2021). The Geological Society of London have an active policy programme, responding to consultations and inquiries in the UK, with opportunities for Fellows to inform these responses.

Work at the science–policy interface involves communicating technical information to non-technical stakeholders, and knowledge of policy-making processes that is often missing from the training of engineering geologists. Delivering the UN SDGs will require increased engagement of engineering geologists, and their professional societies, in policy-level initiatives. This can be supported by building the collaborations described at the start of this section, and embedding governance and an understanding of policy-making processes into the training of engineering geologists.

Conclusions

This paper provides a clear understanding of the role that engineering geology has in delivering UN SDGs. A detailed mapping exercise has been undertaken to review the dependency of all 169 SDG targets on engineering geology knowledge, skills and activities. Examples from the literature and project case studies were used to demonstrate the direct and indirect contribution of engineering geologists to all 17 of the UN SDGs, drawing on experience gained across a range of different geographies, organizations and development contexts. The aim of this approach was to make this exercise globally relevant and in line with the UN SDGs. While this assessment is systematic and detailed, it is by no means considered exhaustive.

As illustrated by Figure 3, engineering geologists clearly have an important role to play in achieving sustainable development globally, primarily through their role in infrastructure development, building resilience and disaster risk reduction, and environmental protection, but also, indirectly, by building equitable and effective communities, and through collaborative and strong partnerships.

Although the study has identified many ways in which engineering geologists are already contributing to the delivery of the UN SDGs, a number of opportunities to strengthen their contribution have also been identified, these include: extending their influence across the project life cycle, and to policy-making; greater consideration of options for decarbonization, the impacts of climate change, and the value of geocapital and geodiversity; training in geoethics, and a greater emphasis on diversity, inclusion and equity within the profession; and increased collaboration and knowledge sharing globally through cross- and multi-disciplinary partnerships, and between industry and academia.

It is hoped that by investigating and articulating the different ways in which engineering geologists contribute to each of the UN SDGs and targets, this paper will enable and empower engineering geologists globally to better communicate the value of their contribution to society, the environment and the economy, and to identify opportunities to increase that impact. Engineering geologists must seek to understand the consequences of their work in terms of sustainable development, and, in so doing, act responsibly and exert their influence to drive positive outcomes in everything that they do.

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Correction notice This paper is now available under an Open Access license.

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References

Adams, C. A. 2017. *The Sustainable Development Goals, Integrated Thinking and the Integrated Report*. International Integrated Reporting Council (IIRC) and Institute of Chartered Accountants of Scotland (ICAS).

Alawneh, R., Ghazali, F., Ali, H. and Sadullah, A.F. 2019. A novel framework for integrating United Nations Sustainable Development Goals into sustainable non-residential building assessment and management in Jordan. *Sustainable Cities and Society*, **49**, 101612, https://doi.org/10.1016/j.scs.2019.101612

Allen, C., Metternicht, G. and Wiedmann, T. 2019. Prioritising SDG targets: assessing baselines, gaps and interlinkages. *Sustainability Science*, **14**, 421–438, https://doi.org/10.1007/s11625-018-0596-8
Bardos, R.P., Bone, B.D., Boyle, R., Ellis, D., Evans, F., Harries, N. and Smith, J.W. 2011. Applying sustainable development principles to contaminated land management using the SuRF-UK framework. *Remediation*, **22**, 77–100, https://doi.org/10.1002/rem.20283
Bardos, R.P., Thomas, H.F., Smith, J.W., Harries, N.D., Evans, F., Boyle, R. and Haslam, A. 2018. The development and use if sustainability criteria in SuRF-UK's sustainable remediation framework. *Sustainability*, **10**, 1781, https://doi.org/10.3390/su10061781
Basiago, A.D. 1999. Economic, social, and environmental sustainability in development theory and urban planning practice. *The Environmentalist*, **19**, 145–161, https://doi.org/10.1023/A:1006697118620
Baynes, F.J., Griffiths, J.S. and Rosenbaum, M.S. 2009. The future of engineering geology. *Geological Society, London, Engineering Geology Special Publications*, **22**, 297–302, https://doi.org/10.1144/EGSP22.26
Baynes, F.J., Parry, S. and Novotný, J. 2020. Engineering geological models, projects and geotechnical risk. *Quarterly Journal of Engineering Geology and Hydrogeology*, **54**, qjegh2020-080,https://doi.org/10.1144/qjegh2020-080
Bohle, M. 2019. *Exploring Geoethics: Ethical Implications, Societal Contexts, and Professional Obligations of the Geosciences*. Palgrave Pivot, Cham, Switzerland.
Brabham, P., Manju, M., Thomas, H., Farr, G., Francis, R., Sahid, R. and Sadasivam, S. 2019. The potential use of mine water for a district heating scheme at Caerau, Upper Llynfi valley, South Wales, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, **53**, 145–158, https://doi.org/10.1144/qjegh2018-213
Brandl, H. 2004. *The Civil and Geotechnical Engineer in Society – Ethical and Philosophical Thoughts, Challenges and Recommendations*. The Deep Foundations Institute, Hawthorne, NJ.
Brandolini, P., Cevasco, A., Capolongo, D., Pepe, G., Lovergine, F. and Del Monte, M. 2018*a*. Response of terraced slopes to a very intense rainfall event and relationships with land abandonment: a case study from Cinque Terre (Italy). *Land Degradation & Development*, **29**, 630–642, https://doi.org/10.1002/ldr.2672
Brandolini, P., Pepe, G., Capolongo, D., Cappadonia, C., Cevasco, A., Conoscenti, C. and Del Monte, M. 2018*b*. Hillslope degradation in representative Italian areas: Just soil erosion risk or opportunity for development? *Land Degradation & Development*, **29**, 3050–3068, https://doi.org/10.1002/ldr.2999
Bryan, B.A., Hadjikakou, M. and Moallemi, E.A. 2019. Rapid SDG progress possible. *Nature Sustainability*, **2**, 999–1000, https://doi.org/10.1038/s41893-019-0422-z
BSI 2016. *PAS 2080:2016: Carbon Management in Infrastructure*. British Standards Institution (BSI), London.
Burford, G., Hoover, E., Velasco, I., Janoušková, S., Jimenez, A., Piggot, G. and Harder, M.K. 2013. Bringing the 'missing pillar' into Sustainable Development Goals: Towards intersubjective values-based indicators. *Sustainability*, **5**, 3035–3059, https://doi.org/10.3390/su5073035
Capello, M.A., Shaughnessy, A. and Caslin, E. 2021. The geophysical sustainability atlas: Mapping geophysics to the UN Sustainable Development Goals. *The Leading Edge*, **40**, 10–24, https://doi.org/10.1190/tle40010010.1
Chapman, T. 2012. Geotechnical risks and their context for the whole project. *In*: Chapman, T., Burland, J., Skinner, H. and Brown, M. (eds) *ICE Manual of Geotechnical Engineering, Volume I*. ICE Publishing, London, 59–73.
Chapman, T. and Marcetteau, A. 2004. Achieving economy and reliability in piled foundation design for a building project. *The Structural Engineer*, **82**, 32–37.
Cisneros-Montemayor, A.M., Moreno-Báez, M., Reygondeau, G., Cheung, W., Crosman, K., González-Espinosa, P. C. and Ota, Y. 2021. Enabling conditions for an equitable and sustainable blue economy. *Nature*, **591**, 396–401, https://doi.org/10.1038/s41586-021-03327-3
Cook, J. 2019. Engineering geology research and rural access in support of United Nations Sustainable Development Goals. *In*: Shakoor, A. and Cato, K. (eds) *IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018 – Volume 6*. Springer Nature, Cham, Switzerland, 19–25, https://doi.org/10.1007/978-3-319-93142-5_3
Czerwinska, D. 2017. *Green Building: Improving the lives of billions by helping to achieve the UN Sustainable Development Goals*. World Green Building Council, London, https://www.worldgbc.org/news-media/green-building-improving-lives-billions-helping-achieve-un-sustainable-development-goals
DEFRA 2019. *Environment Bill Summer Policy Statement: July 2019*. Department for Environment Food & Rural Affairs (DEFRA), London, https://www.gov.uk/government/publications/draft-environment-principles-and-governance-bill-2018/environment-bill-summer-policy-statement-july-2019
Di Capua, G. and Peppoloni, S. 2019. *Definition of Geoethics*. International Association for Promoting Geoethics, http://www.geoethics.org/definition
Di Capua, G., Bobrowsky, P.T., Kieffer, S.W. and Palinkas, C. 2021. Introduction: geoethics goes beyond the geoscience profession. *Geological Society, London, Special Publications*, **508**, 1–11, https://doi.org/10.1144/SP508-2020-191
Dobbs, R., Pohl, H., Lin, D.-Y., Mischke, J., Garemo, N., Hexter, J. and Nanavatty, R. 2013. *Infrastructure Productivity: How to save $1 Trillion a Year*. McKinsey Global Institute.
Dottridge, J. and Smith, J. 2020. Editorial 2020. *Quarterly Journal of Engineering Geology and Hydrogeology*, **54**, 1–2, https://doi.org/10.1144/qjegh2020-004
Doyle, M.R., Thalmann, P. and Parriaux, A. 2019. Embodied energy and lifecycle costs: Questioning (mis)conceptions about underground construction. *Buildings*, **9**, 188, https://doi.org/10.3390/buildings9080188
Elkington, J. 1994. Towards the sustainable corporation: Win-win-win business strategies for sustainable development. *California Management Review*, **36**, 90–100, https://doi.org/10.2307/41165746
Evans, D.J., Shaw, R.P. and Stephenson, M.H. 2009. The present and future use of 'land' below ground. *Land Use Policy*, **26S**, S302–S316, https://doi.org/10.1016/j.landusepol.2009.09.015
Fookes, P.G. 1997. Geology for engineers: the geological model, prediction and performance. *Quarterly Journal of Engineering Geology and Hydrogeology*, **30**, 293–424, https://doi.org/10.1144/GSL.QJEG.1997.030.P4.02
Fordyce, F.M. and Campbell, S.D. 2019. The geoscience context for Europe's urban sustainability – lessons from Glasgow and beyond (CUSP): Preface. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **108**, 119–122, https://doi.org/10.1017/S1755691018000373
Fox, N., Graham, L.J., Eigenbrod, F., Bullock, J.M. and Parks, K.E. 2020. Incorporating geodiversity in ecosystem service decisions. *Ecosystems and People*, **16**, 151–159, https://doi.org/10.1080/26395916.2020.1758214
Geological Society of London 2020.*Geoscience for the Future*. Geological Society, London, https://www.geolsoc.org.uk/~/media/shared/documents/education%20and%20careers/Resources/Posters/Geoscience%20for%20the%20Future%20poster.pdf?la=en
Gill, J.C. 2017. Geology and the Sustainable Development Goals. *Episodes*, **40**, 70–76, http://dx.doi.org/10.18814/epiiugs/2017/v40i1/017010
Gill, J.C. and Smith, M. (eds) 2021. *Geosciences and the Sustainable Development Goals*. Sustainable Development Goals Series. Springer Nature, Cham, Switzerland.
Gill, J.C., Taylor, F.E., Duncan, M.J., Mohadjer, S., Budimir, M., Mdala, H. and Bukachi, V. 2021. Building sustainable and resilient communities – Recommended actions for natural hazard scientists. *Natural Hazards and Earth System Sciences*, **21**, 187–202, https://doi.org/10.5194/nhess-21-187-2021
Gluckman, P. 2016. The science–policy interface. *Science*, **353**, 969, https://doi.org/10.1126/science.aai8837
Gordon, J.E. and Barron, H.F. 2013. The role of geodiversity in delivering ecosystem services and benefits in Scotland. *Scottish Journal of Geology*, **49**, 41–58, https://doi.org/10.1144/sjg2011-465
Goubran, S. 2019. On the role of construction in achieving the SDGs. *Journal of Sustainability Research*, **1**, e190020, https://doi.org/10.20900/jsr20190020
Gould, J.P. 1995. Geotechnology in dispute resolution: The Twenty-Sixth Terzaghi Lecture. *Journal of Geotechnical Engineering*, **121**, 523–534, https://doi.org/10.1061/(ASCE)0733-9410(1995)121:7(523)
Gyadu-Asiedu, W., Ampadu-Asiamah, A. and Fokuo-Kusi, A. 2021. A framework for systemic sustainable construction industry development (SSCID). *Discover Sustainability*, **2**, 25, https://doi.org/10.1007/s43621-021-00033-y
Hawkes, J. 2001. *The Fourth Pillar of Sustainability: Culture's Essential Role in Public Planning*. Common Ground Publishing, Sydney, Australia.
Hosseini, S.M., Pons, O. and de la Fuente, A. 2019. Suitability of different decision-making methods applied for analysing sustainable post-disaster temporary housing. *In*: Asgary, A. (ed.) *Resettlement Challenges for Displaced Populations and Refugees*. Sustainable Development Goals Series. Springer Nature, Cham, Switzerland, 207–220.
IAEG 1992. *International Association for Engineering Geology and the Environment Statutes*. International Association for Engineering Geology and the Environment (IAEG).
IGS 2019. *Global Sustainable Development Report 2019: The Future is Now – Science for Achieving Sustainable Development*. Independent Group of Scientists appointed by the United Nations Secretary-General, New York.
IISD 2021. *Sustainable Development*. International Institute for Sustainable Development (IISD), Winnipeg, Manitoba, Canada, https://www.iisd.org/about-iisd/sustainable-development
Institution of Civil Engineers 2020. *Maximising Social Value from Infrastructure Projects*. ICE Publishing, London.
InterAcademy Partnership 2019. *Improving Scientific Input to Global Policymaking, with a Focus on the UN Sustainable Development Goals*. The InterAcademy Partnership, Washington, DC.
International Council for Science 2017. *A Guide to SDG Interactions: From Science to Implementation*. International Science Council, Paris.
IPCC 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.
I3P 2021. Dig to Share. Infrastructure Industry Innovation Partnership (I3P), https://www.i3p.org.uk/en/custom/i3pprojects/view/938
Kessler, H., Wood, B., Morin, G., Gakis, A., McArdle, G., Dabson, O. and Dearden, R. 2015. Building Information Modelling (BIM): A route for geological models to have real world impact. *In*: Proceedings of the 2015

Geological Society of America (GSA) Annual Meeting. Geological Society of America, Boulder, CO, 13–18.
Kyaw, H., Cho, T.O., Tun, N.Z. and Day, A.W. 2019. Landslide hazard in Chin State: A case study in Hakka and its environs. *In*: James H. (ed.) *Population, Development, and the Environment*. Palgrave Macmillan, Singapore, 195–213.
Littig, B. and Grießler, E. 2005. Social sustainability: a catchword between political. *International Joirnal of Sustainable Development*, **8**, 65–79, https://doi.org/10.1504/IJSD.2005.007375
Littlejohn, G.S., Cole, K. and Mellors, T.W. 1994. Without site investigation ground is a hazard. *Proceedings of the Institution of Civil Engineers*, **102**, 72–78.
Lubchenco, J., Barner, A.K., Cerny-Chipman, E.B. and Reimer, J.N. 2015. Sustainability rooted in science. *Nature Geoscience*, **8**, 741–745, https://doi.org/10.1038/ngeo2552
MacLeamy 2004. *Collaboration, Integrated Information, and the Project Lifecycle in Building Design, Construction and Operation*. The Construction Users Roundtable (CURT).
Maes, M.J., Jones, K.E., Toledano, M.B. and Milligan, B. 2019. Mapping synergies and trade-offs between urban ecosystems and the sustainable development goals. *Environmental Science & Policy*, **93**, 181–188, https://doi.org/10.1016/j.envsci.2018.12.010
Mansell, P., Philbin, S.P., Broyd, T. and Nicholson, A. 2019*a*. Assessing the impact of infrastructure projects on Global Sustainable Development Goals. *Engineering Sustainability*, **173**, 196–212, https://doi.org/10.1680/jensu.19.00044
Mansell, P., Philbin, S. and Konstantinou, E. 2019*b*. *Using 'Creating Shared Value' to Support Measurement of the Sustainable Development Goal (SDG) Targets for Infrastructure Projects*. European Academy of Management (EURAM), Lisbon.
Mensah, J. 2019. Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review. *Cogent Social Sciences*, **5**, 1, https://doi.org/10.1080/23311886.2019.1653531
Monaghan, A.A., Starcher, V. *et al.* 2021. Drilling into mines for heat: geological synthesis of the UK Geoenergy Observatory in Glasgow and implications for mine water heat resources. *Quarterly Journal of Engineering Geology and Hydrogeology*, https://doi.org/10.1144/qjegh2021-033
Mora, G. 2013. The need for geologists in sustainable development. *GSA Today*, **23**, 36–37, https://doi.org/10.1130/GSATG185GW.1
Moyer, J.D. and Bohl, D.K. 2019. Alternative pathways to human development: Assessing trade-offs and synergies in achieving the Sustainable Development Goals. *Futures*, **105**, 199–210, https://doi.org/10.1016/j.futures.2018.10.007
Nathanail, C. P. 2013. Engineering geology of sustainable risk-based contaminated land management. *Quarterly Journal of Engineering Geology and Hydrogeology*, **46**, 6–29, https://doi.org/10.1144/qjegh2011-071
NERC 2021. *Environmental Risks to Infrastructure Innovation Programme*. Natural Environment Research Council (NERC), Swindon, UK, https://nerc.ukri.org/innovation/activities/infrastructure/envrisks/
Nilsson, M., Griggs, D. and Visbeck, M. 2016. Policy: Map the interactions between Sustainable Development Goals. *Nature*, **534**, 320–322, https://doi.org/10.1038/534320a
Osinubi, K.J., Eberemu, A.O., Gadzama, E.W. and Ijimdiya, T.S. 2019. Plasticity characteristics of lateritic soil treated with *Sporosarcina pasteurii* in microbial-induced calcite precipitation application. *SN Applied Sciences*, **1**, 829, https://doi.org/10.1007/s42452-019-0868-7
Pantelidou, H., Nicholson, D. and Gaba, A. 2012. Sustainable geotechnics. *In*: Chapman, T., Burland, J., Skinner, H. and Brown, M. (eds) *ICE Manual of Geotechnical Engineering, Volume I*. ICE Publishing, London, 125–136, https://doi.org/10.1680/moge.57074
Patton, A.M., Farr, G., Boon, D.P., James, D.R., Williams, B., James, L. and White, D. 2020. Establishing an urban geo-observatory to support sustainable development of shallow subsurface heat recovery and storage. *Quarterly Journal of Engineering Geology and Hydrogeology*, **53**, 49–61, https://doi.org/10.1144/qjegh2019-020
Pelling, M., Maskrey, A., Ruiz, P., Hall, P., Peduzzi, P., Dao, Q.H. and Kluser, S. 2004. *Reducing Disaster Risk: A Challenge for Development*. United Nations, New York.
Pickering, C.M. and Byrne, J. 2014. The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early career researchers. *Higher Education Research and Development*, **33**, 534–548, https://doi.org/10.1080/07294360.2013.841651
Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P. and Cooke, S.J. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. *Biological Reviews*, **94**, 849–873, https://doi.org/10.1111/brv.12480
Sachs, J. 2015. *The Age of Sustainable Development*. Columbia University Press, New York.
Sachs, J., Kroll, C., Lafortune, G., Fuller, G. and Woelm, F. 2021. *The Decade of Action for the Sustainable Development Goals: Sustainable Development Report 2021*. Cambridge University Press, Cambridge, UK.
Schrodt, F., Bailey, J.J., Kissling, W.D., Rijsdijk, K.F., Seijmonsbergen, A.C., Ree, D.V. and Brilha, J. 2019. To advance sustainable stewardship, we must document not only biodiversity but geodiversity. *Proceedings of the National Academy of Sciences of the United States of America*, **116**, 16 155–16 158, https://doi.org/10.1073/pnas.1911799116
Shi, L., Han, L., Yang, F. and Gao, L. 2019. The evolution of sustainable development theory: Types, goals, and research prospects. *Sustainability*, **11**, 7158, https://doi.org/10.3390/su11247158
Singh, G.G., Cisneros-Montemayor, A.M., Swartz, W., Cheung, W., Guy, J.A., Kenny, T.-A. and Asch, R. 2018. A rapid assessment of co-benefits and trade-offs among Sustainable Development Goals. *Marine Policy*, **93**, 223–231, https://doi.org/10.1016/j.marpol.2017.05.030
STC MG 2021. *Position Paper for the 2021 High-Level Political Forum*. Scientific and Technological Community Major Group (STC MG) of the United Nations.
Stewart, I.S. and Gill, J.C. 2017. Social geology – integrating sustainability concepts into Earth sciences. *Proceedings of the Geologists' Association*, **28**, 165–172, https://doi.org/10.1016/j.pgeola.2017.01.002
Stibbe, D. and Prescott, D. 2016. *An Introduction to Multi-Stakeholder Partnerships*. The Partnering Initiative, Oxford, UK.
Terrington, R.L., Thorpe, S., Kessler, H., Bidarmaghz, A., Choudhary, R., Yuan, M. and Bricker, S. 2019. Making geology relevant for infrastructure and planning. *In*: DeJong, M.J., Schooling, J.M. and Viggiani, G.M.B. (eds) International Conference on Smart Infrastructure and Construction 2019 (ICSIC): Driving Data-Informed Decision-Making. ICE Publishing, London, 403–409.
Thacker, S., Adshead, D., Morgan, G., Crosskey, S. and Bajpai, A. 2018. *Infrastructure: Underpinning Sustainable Development*. United Nations Office for Project Services (UNOPS), Copenhagen.
The Economist 2005. Blue skies thinking. *The Economist*, 20 August.
The Economist Intelligence Unit 2019. *The Critical Role of Infrastructure for the Sustainable Development Goals*. The Economist Intelligence Unit Ltd, London.
Turner, A.K., Kessler, H. and Van der Meulen, M.J. (eds) 2021. *Applied Multidimensional Geological Modeling: Informing Sustainable Human Interactions with the Shallow Subsurface*. Wiley-Blackwell, Hoboken, NJ.
UCLG 2010. *Culture: Fourth Pillar of Sustainable Development. Policy Statement of the UCLG Executive Bureau*. United Cities and Local Governments (UCLG).
UNCED 1992. *United Nations Conference on Environment and Development (UNCED). Agenda 21, Rio Declaration, Forest Principles*. United Nations, New York.
UNDP 2004. *Reducing Disaster Risk: A Challenge for Development*. United Nations Development Programme (UNDP), New York.
UNDP 2013. *Political Champions: No Development Without Disaster Risk Reduction*. United Nations Development Programme (UNDP), New York, https://reliefweb.int/report/world/political-champions-no-development-without-disaster-risk-reduction
UNDRR 2015*a*. *Sendai Framework for Disaster Risk Reduction 2015–2030*. United Nations Office for Disaster Risk Reduction, Geneva Switzerland.
UNDRR 2015*b*. *Disaster Risk Reduction and Resilience in the 2030 Agenda for Sustainable Development*. United Nations Office for Disaster Risk Reduction, Geneva Switzerland.
UNEP 2019. *Measuring Progress: Towards Achieving the Environmental Dimension of the SDGS*. United Nations Environment Programme (UNEP), Nairobi.
UNFCCC 2015. Paris Agreement. United Nations Framework Convention on Climate Change, https://unfccc.int/sites/default/files/english_paris_agreement.pdf
United Nations 2000. *United Nations Millenium Declaration. Resolution Adopted by the General Assembly, 55/2*. United Nations, New York.
United Nations 2015. *Transforming our World: The 2030 Agenda for Sustainable Development*. United Nations, New York.
United Nations 2017. *New Urban Agenda*. United Nations, New York.
United Nations 2022. *Sustainable Development Goals Communications Materials*, United Nations, New York, https://www.un.org/sustainabledevelopment/news/communications-material/
Van Ree, C. and Beukering, P.V. 2016. Geosystem services: A concept in support of sustainable development of the subsurface. *Ecosystem Services*, **20**, 30–36, https://doi.org/10.1016/j.ecoser.2016.06.004
van Staveren, M. 2006. *Uncertainty and Ground Conditions: A Risk Management Approach*. Elsevier, Amsterdam.
von der Tann, L., Metje, N., Admiraal, H. and Collins, B. 2018. The hidden role of the subsurface for cities. *Proceedings of the Institution of Civil Engineers – Civil Engineering*, **171**, 31–37, https://doi.org/10.1680/jcien.17.00028
WCED 1987. *Report of the World Commission on Environment and Development: Our Common Future (Bruntland Report). United Nations General Assembly Document A/42/427*. World Commission on Environment and Development (WCED).
Woetzel, J., Garemo, N., Mischke, J., Hjerpe, M. and Palter, R. 2016. *Bridging Global Infrastructure Gaps*. McKinsey Global Institute.