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Sustainable Development Goals and the Geosciences: A Review

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The 17 United Nations Sustainable Development Goals (SDGs) collectively represent the global population's ambition to improve the wellbeing of Earth and its inhabitants by 2030. The ambitious goals require that a dedicated, focused, and integrated effort is taken—now. The geoscientific community is well positioned to positively directly influence many of the SDGs, notably SDGs 7 (Affordable Energy), 11 (Sustainable Cities) and 13 (Climate Action), and may also directly or indirectly contribute to all other SDGs. In this contribution, I systematically review the SDGs in the framework of the broader geosciences. Firstly, I outline the concept of the SDGs and their indicators, before linking them to specific geoscientific disciplines illustrated with case studies. Finally, I present some of the ongoing developments in the geosciences that need to be clearly tied to the global SDG ambitions.

Keywords: sustainability, digital earth, digital geoscience, geological society, developing countries, global change, climate change

HIGHLIGHTS

- Geoscientists can significantly contribute to fulfilling the UN Sustainable Development Goals (SDGs) by 2030.
- This applies at individual, institutional, national and international levels.
- Geoscientists provide critical input for SDGs 7 (Affordable Energy), 11 (Sustainable Cities) and 13 (Climate Action).
- The ongoing digitalization revolution provides momentum to positively influence SDGs and to quantitatively measure impacts of measures taken.

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INTRODUCTION

In 2015 the United Nations (UN) countries agreed on 17 Sustainable Development Goals (SDGs) that should guide sustainable development from 2015 to 2030. The interlinked SDGs oversee 169 specific targets that must be reached to, amongst others, end global poverty and hunger, facilitate economic growth and social development and protect the environment (Gray and Crofts, 2022). Social, environmental and economic sustainable development is the ultimate goal and progress is monitored over time using 232 indicators (Fritz et al., 2019). Humankind is using more resources than ever before. A paradigm shift is needed to evaluate and maintain Earth's sustained viability for life. Stewart (2016) advocates sustainable geoscience with strong geoscientist involvement and collaboration within and outside the geosciences for maximum effect. SDGs are inter-linked, often in pairs with a high mutual connection where synergies exist (Pradhan et al., 2017; Fuso Nerini et al., 2019). In effect, activity to address one SDG may generate positive or negative effect in another and global partnerships are required to implement the SDGs across individuals, institutions, governments, and the global community.

Geoscientists have, like all other inhabitants of planet Earth, a strong role to play to reach the ambitious SDG targets by 2030 (Gill and Smith, 2021). Geoscientists are used to working with inter-linked processes and trying to understand the entire system, making geoscientific competence critical to reach the SDGs. Another benefit is the geoscientists' ability to think over longer time-scales (i.e., millions of years)—deep-time paleoclimatology reveals how the planet's climate changed in the past due to natural variability such as the rapidly warming period around the Paleocene-Eocene Thermal Maximum (PETM; e.g., McInerney and Wing, 2011). This knowledge can subsequently be used to better comprehend ongoing climate change and guide future climate predictions. Furthermore, many geoscientific disciplines are directly involved with the SDGs–notably energy and mineral production, geohazard mitigation and groundwater exploration. This linkage of geoscience disciplines to SDGs was initially mapped by the non-profit organization Geology for Global Development (GFGD; Gill, 2017), expanded on by a comprehensive textbook (Gill and Smith, 2021).

National geological surveys are a natural link between geoscientists and society. National geological surveys, some of which have been operating for over 100 years, have broad mandates including geological mapping, facilitating sustainable resource extraction, mitigation of geohazards and provision of geodata and knowledge for land use planning and other societal needs. Hill et al. (2020) present a series of papers focusing on the changing role of national geological surveys at a time when geohazards increase due to ongoing climate change, staffing in surveys is in decline and big data represents a vast potential to effectively provide geoscientific data and knowledge to the society. Smelror (2020) provides a broad overview of the global mega-trends affecting national geological surveys and predicts a geoscientific world in 2058—with CO_2 free energy sources, a greenstone age with usage of all the elements in the periodic table, high-resolution 3D imagery of the entire earth and 4D models of urban areas to support smart cities. Notably, Smelror (2020) highlights the SDGs as key guidelines for geoscientists well into the future. The way to a sustainable planet by 2058 supporting an ever growing population is long, with set-backs such as the global COVID-19 pandemic (Nundy et al., 2021) or the Russian war in the Ukraine (Pereira et al., 2022) delaying the progress and threatening us to reach the SDG targets by 2030.

Many geoscience sub-disciplines conducted mapping of SDGs to their activity, including engineering geology (Lagesse et al., 2022), geophysics (Capello et al., 2021), mining (Sonesson et al., 2016) and the petroleum industry (UNDP et al., 2017). Most of these link SDGs to their own professions, with some links to other environmental disciplines. As pointed out by Stewart and Gill (2017), however, geoscientists need to work together with social sciences (i.e., "Social Geology") to be directly engaged in discussions on sustainable development and directly contribute to addressing many of society's challenges through the SDGs.

A systematic review mapping how various geoscientific professions address SDGs is presently missing. In this contribution I first review the largest impacts that geoscientists have had on global development. I then outline the broad range of professions geoscientists are involved in and map these specifically to the 17 SDGs, using case studies to illustrate present linkage. Finally, I consider future development and identify general trends along which geoscientists can significantly impact the ambitious SDGs.

SUSTAINABLE DEVELOPMENT GOALS AND EARTH SCIENCES

The 2030 Agenda for Sustainable Development was adopted by 193 United Nations (UN) member states in September 2015—introducing the 17 integrated SDGs (**Figure 1**). The 17 SDGs oversee 169 targets that aim to make the planet a better place by 2030 and ensure social, economic and environmental sustainability (United Nations, 2022). As stated by the United Nations (2022), the SDGs *"recognize that ending poverty and other deprivations must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth–all while tackling climate change and working to preserve our oceans and forests."*

The SDGs build on previous work by the UN and its member states, notably the Millennium Development Goals (MDGs) that were targeted from 2000 to 2015 (Sachs, 2012). The implementation of SDGs is closely followed by the UN's Division for Sustainable Development Goals (DSDG) who publish annual Progress Reports and a quadrennial Global Sustainability Development report. The SDGs are not legally binding for the signatories, but the simplicity and clear goals facilitate greater involvement from people, institutions, and authorities. Furthermore, the 17 SDGs are integrated–with changes in one SDG generating effects on others. Early on, it was recognized that a siloed approach to SDGs would not be adequate and that scientific work would be crucial to understand and address the complex relationships in a closely-linked human-environment system (Messerli et al., 2019).

Together with the adoption of the SDGs, two other milestone global agreements were agreed to in 2015—the Sendai Framework for Disaster Risk Reduction (SFDRR) and the Paris Agreement on Climate Change (PACC). The SFDRR's main purpose is to adopt measures that prevent the creation of new risks, reduce existing risks, and increase resilience. The PACC is a legally binding agreement to keep the rise in mean global temperatures to well below 2°C above pre-industrial levels, through among others reducing atmospheric CO_2 emissions. Together these three agreements (i.e., SDG, SFDRR, PACC) highlighted the global consensus that business as usual is not an option anymore and that the trajectory must be changed–and that

FIGURE 1 | Overview of the 17 Sustainable Development Goals, highlighting the geoscience links based on the number of categories addressing them as listed in **Table 1**. SDG icons courtesy of United Nations. The full list of goals and related targets is available from United Nations (2022).

geoscientists are crucial to achieving the goals for all these agreements (Gill and Bullough, 2017).

SUSTAINABLE DEVELOPMENT GOALS: INDICATORS

Indicators are necessary in any effort to change anything in order to quantify if targets are being met and that progress is made in the right direction. Berger (1997) introduced the concept of 27 geoindicators ranging from coral reef growth patterns, shoreline position to volcanic unrest. Each geoindicator reflects a broad range of environmental changes, for instance changing climate (i.e., air and water temperature), hydrology, faulting and near-surface magmatism.

In the context of the SDGs, a preliminary set of 330 indicators were introduced in March 2015 to assess sustainable development (Hák et al., 2016). However, the indicators need to undergo a phase of conceptualization and operationalization to reduce ambiguity and truly assess progress in the individual SDGs (Hák et al., 2016). This applies at both indicator level (Janoušková et al., 2018) and at national level–with Schmidt-Traub et al. (2017) presenting the SDG Index and Dashboard tools facilitating access to relevant country-level data. These tools facilitate "on-the-road" adjustments and provide interlinkage of several SDGs that may influence a single indicator in different ways. Such interactions and synergies between individual SDGs were analyzed by Pradhan et al. (2017) at the global scale, identifying both synergies (where progress in one SDG positively influences progress in another) and trade-offs (where progress in one SDG negatively influences progress in another).

New indicators are often proposed, for instance for oceans (Rickels et al., 2016). In recent years, there are incentives to use big data for more efficient indicator tracking (e.g., MacFeely, 2019; Guo et al., 2022) or the inclusion of citizen science (Fritz et al., 2019). However, as pointed out by Scown (2020), the SDGs need geosciences to be more strongly integrated. An obvious downside of the country-by-country indicators discussed above is that geological boundaries do not follow political boundaries. Geohazards such as floods, earthquakes or volcanic eruptions, for instance, often cross-country boundaries. In this context, incorporating geosciences in the SDG debate and considering units as Earth subsystems rather than countries is preferred (Scown, 2020).

GEOSCIENTISTS AND THE SDGS

Geosciences cover a broad field with activity spanning from the Earth's core to distant planets and across Earth's spheres–geosphere, hydrosphere, atmosphere, cryosphere, and biosphere. Furthermore, geoscientists work with complex systems and processes, with the Earth itself as a sum of the inter-linked cycles and processes the most complex of them all. Geoscientific professions may be curiosity-driven to decipher and understand how the Earth system works at present, has functioned in the past, and will likely function in the future as the boundary conditions change. Geoscientists also have a vital applied role with direct societal relevance, having critical roles in, for instance, geohazard mitigation, energy production, mineral extraction and exploration and production of the most important resource of all—groundwater. As such, the geoscientific community is well poised to contribute significantly to the global effort of reaching the SDG goals by 2030—if geoscientists work across sectors (industry, academia, government and society) and in active partnerships with other disciplines (e.g., engineering, health, ecology, social sciences).

Figure 2 illustrates the broad range of geoscientific disciplines and how these relate to the SDGs. More details and case studies are provided below, but it is worth to highlight some of the geoscience to SDG mapping conducted since the SDGs were adopted in 2015. Gill (2017) systematically mapped the dependence of SDGs on the geosciences and provided the first matrix linking geoscience professions to the SDGs. Gill and Bullough (2017) build on this and specifically outline how geoscientists can engage in contributing to the SDGs targets, as well as the SFDRR and PACC agreements.

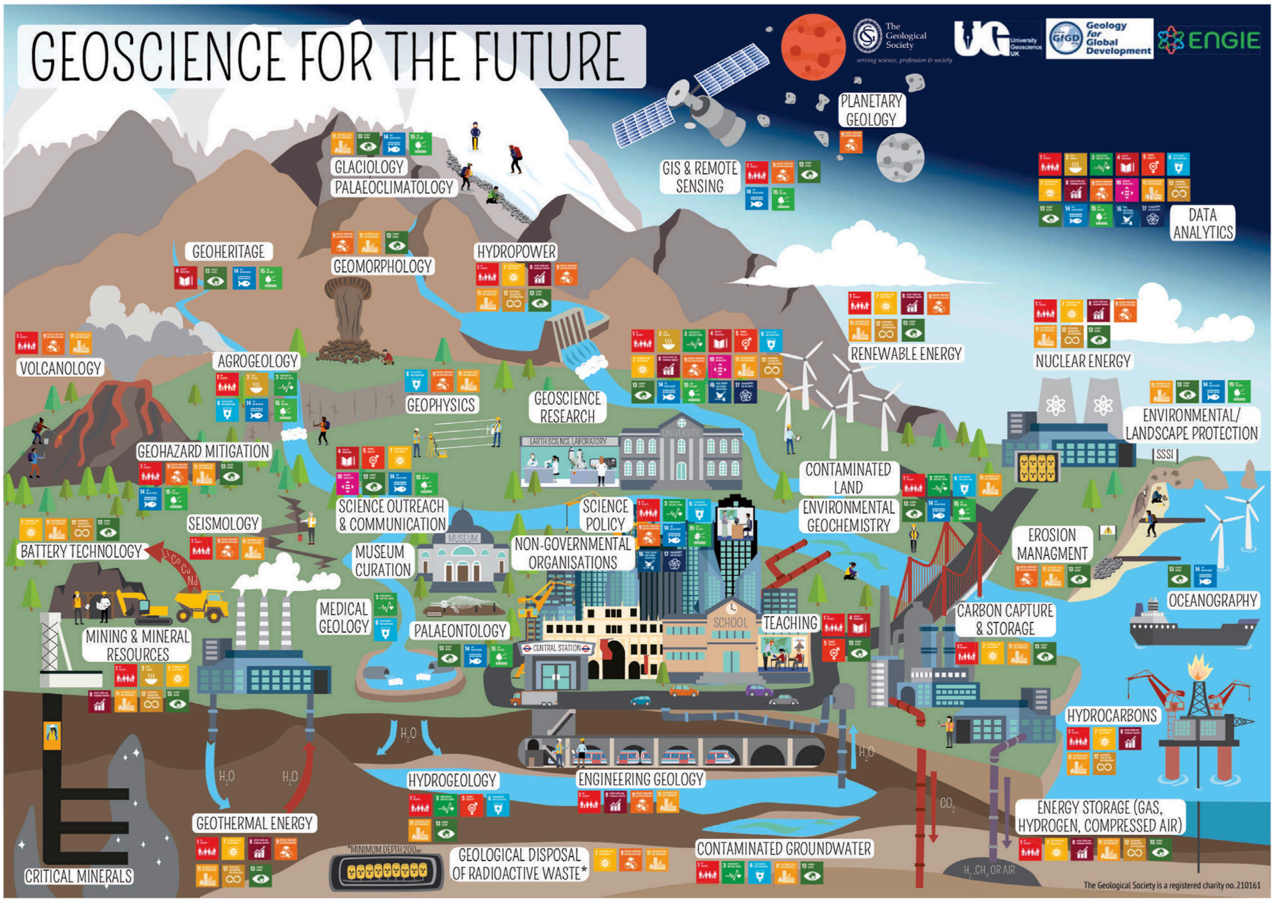

FIGURE 2 | Synthesis of geoscientific categories mapped to the SDGs. Figure from The Geological Society (2021), licensed under CC BY-NC-ND 4.0. Refer to **Table 1** for details.

Schrodt et al. (2019) advocates the use of systematic geodiversity variables in addition to biodiversity ones. Various international institutions affiliated to the UN published reports on how SDGs are linked to a particular industry's activity, for instance the mining industry (Sonesson et al., 2016) or the oil and gas industry (UNDP et al., 2017). Capello et al. (2021) maps the SDGs to geophysics, highlighting the ongoing energy transition affecting the petroleum industry and the need for a technology and knowledge transfer during this transition. Finally, Gill and Smith (2021) compiled a comprehensive book that matches the 17 SDGs to geoscientific activities, richly illustrated with case studies.

As is evident from **Figure 2**, geoscientists play a crucial role in a range of fields. Arguably the most significant contribution of geoscientists relates to securing affordable energy for the global population. The first commercial oil well drilled in Pennsylvania in 1859 marks the start of the industrial revolution which included exponential use of coal for steam engines and eventually the use of gasoline vehicles. By 2020 fossil fuels coal, oil and gas accounted for 84% of the global energy mix (Ritchie et al., 2022). Geoscientists are crucial in both finding and producing these resources. Oil and gas exploration contributed to many technological breakthroughs, notably 3D seismic technology [referred to as the geological "Hubble" by Cartwright and Huuse (2005), the use of unconventional resources like shale gas and gas injection that paves the way for geological CO_2 storage.

However, the global population's long-term demand and thirst for cheap and energy-intensive fossil fuels is not without challenges. Already in the 1970s, Von Engelhardt et al. (1976) pointed out that the explosive growth in the human population and *per capita* usage of nonrenewable fossil fuel and mineral resources marks a global ecological crisis. The current global climate crisis is largely driven by human overuse of fossil fuels for both energy and transportation, leading to increasing greenhouse gas emissions and global climate change. This is highlighted in the latest Intergovernmental Panel on Climate Change (IPCC) report (Portner et al., 2022), which also highlights how climate change mitigation measures uses the SDGs in its optimization. While it is not realistic to rapidly cut fossil fuel usage globally until cost-effective alternatives are available, geoscientists in the petroleum industry can certainly contribute to this energy transition. Concrete examples of how the petroleum industry can mitigate global greenhouse gas emissions includes large-scale carbon capture and storage (CCS; Bui et al., 2018; Butt et al., 2012; Michael et al., 2010), reduction in energy usage of current activity (i.e., improved energy efficiency) and investment and transition to renewable energy sources.

In **Table 1**, I provide a matrix matching the main geoscientific categories with the SDGs, before describing these in more detail below. This is structured based on the geoscientific activities rather than on the SDGs themselves, reflecting the geoscientist' strong ability to integrate multi-scale and multi-physical data to contribute to several SDGs.

At the broadest level, the number of geoscientific categories suggests that three SDGs, namely, SDG1 (no poverty), SDG11 (sustainable cities and communities) and SDG13 (climate action) have the strongest geoscience link (**Figure 3A**). Six SDGs (SDGs 7, 8, 9, 12, 14 and 15) are also covered by a significant number of geoscience activities, while the remaining eight SDGs have a link to less than ten geoscientific categories. Nonetheless, even these are critical. Conversely, most individual geoscientific categories address 3-8 SDGs (**Figure 3B**). Geoscience research and data analytics address all the SDGs, while planetary geology is only linked to SDG9 (innovation).

More importantly than how many SDGs are addressed by how many geoscientific categories are the case studies highlighted below.

Geohazards

Arguably the largest positive impact that geosciences have had on society relates to how we humans deal with geohazards. This includes understanding the earth processes forming the hazard itself, mitigating against its impacts and, in many cases, monitoring and predicting the geohazard. While the number of reported natural disasters rose substantially from 1970 to 2019 (**Figure 4**)—a trend that is likely to continue as the global climate changes (e.g., Van Aalst, 2006)—the number of fatalities associated with geohazards has decreased substantially from 1900 to 2020 (**Figure 5**). Given the exponential increase in the global population during the same period this represents a major achievement strongly linked to sound geoscientific work. Nonetheless, 10,000–20,000 people still die each year due to geohazards (**Figure 5**). Further focus, amongst others through the SFDRR (Aitsi-Selmi et al., 2015), is required to monitor risks, educate people at risk, reduce risk factors and mitigate impacts of natural disasters.

Geohazard Mitigation (SDG 1, 9, 11, 13, 14, 15)

As outlined above, geoscientists have over the past century contributed to significantly reducing the deaths from natural hazards. Geohazards directly contribute to 6 SDGs, namely, 1, 9, 11, 13, 14 and 15 (**Table 1**; **Figure 2**).

In the current century, the increased use of earth observation (EO) systems further contributes to monitoring and modeling geohazards at different scales. EO observations comprise different sensors (SAR, LiDAR, optical, multispectral) and platforms (from satellites to unmanned aerial vehicles—UAVs) and can provide both spatial and temporal coverage, with a number of case studies presented in the special volume of Tomás and Li (2017).

Shugar et al. (2021) present a case study combining satellite and ground observation to characterize a massive rock and ice avalanche in the Indian Himalaya from 2021. Zheng et al. (2021) present a case study utilizing GIS data along a Chinese railway section affected by both changing permafrost and other geohazards. Mansour et al. (2022) specifically study a flash flood strategy, linking morphometric parameters of the basin to mitigation strategies and thus reduction of hazards.

One of the key recent developments is the broad application of UAVs in the entire life cycle–from understanding hazard potential to crisis management. Antoine et al. (2020) provide a comprehensive review of UAV usage by geoscientists in the context of geohazards with well-illustrated case studies, highlighting that future developments should also incorporate deep learning to extract more information from UAV and potentially satellite data.

On a broader scale, Saunders et al. (2020) outline how one of the world's most geohazard-prone countries, New Zealand, implements the Sendai Framework, the SDGs and the Paris Agreement into its national governance and legislation, with mixed success.

Volcanology (SDG 1, 9, 11)

Volcanoes cause catastrophic damage at the local, regional, and global scale and directly influence SDGs 1, 9 and 11 (**Table 1**; **Figure 2**).

The extreme nature and negative impact of volcanic eruptions is well known, with predictions largely relying on the monitoring network in place and the nature of the eruptions. Many communities near volcanoes need to be resilient in the face of multiple volcanic eruptions, as demonstrated for instance in the Philippines (German et al., 2022).

Living with volcanoes also provides some benefits. Not only do volcanoes enrich soils and carbon stocks with volcanic ash (Tonneijck et al., 2010), but volcanic features also form the basis of many global geoparks (Casadevall et al., 2019). Kelman and Mather (2008) further outline some of the benefits of living near volcanoes despite the eruption risk–primarily related to access to high quality soil and reliable water supply. One of the key findings of their study is that communities near volcanoes can, and often do, develop a sustainable livelihoods approach. In essence, this is the communities' ability to recover from (semi-) regular stress and shocks caused by the volcano.

Seismology (SDG 1, 9, 11)

Earthquakes cause considerable damage and directly influence SDGs 1, 9 and 11 (**Table 1**; **Figure 2**).

Mitigation for earthquakes is highly dependent on earthquake-resistant infrastructure design (e.g., Takagi and Wada, 2019) and its implementation in the building code

TABLE 1 | Mapping sustainable development goals to geoscientific categories. Inspired by Gill (2017), Gill and Smith (2021) and The Geological Society (2021), updated with the categories medical geology, agrogeology, data analytics and geoheritage.

Categories	Sustainable development goals (SDGs)																		Selected references
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17		
	No poverty	Zero hunger	Good health and well being	Quality education	Gender equality	Clean water and sanitation	Affordable and clean energy	Decent work and economic growth	Industry, innovation and infrastructure	Reduced inequalities	Sustainable cities and communities	Responsible consumption and production	Climate action	Life below water	Life on land	Peace, justice and strong institutions	Partnerships for the goals	Number of matched SDGs per category	
Geohazards																			
Geohazard mitigation (SDG 1, 9, 11, 13, 14, 15)	X								X		X		X	X	X			6	Tomás and Li (2017), Antoine et al. (2020), Zheng et al. (2021), Mansour et al. (2022), Shugar et al. (2021)
Volcanology (SDG 1, 9, 11)	X								X		X							3	Tonneijck et al. (2010), Casadevall et al. (2019)
Seismology (SDG 1, 9, 11)	X								X		X							3	Calais et al. (2022), Takagi and Wada (2019), Saunders and Becker (2015)
Geomorphology (SDG 9, 11, 13)									X		X		X					3	Chelli et al. (2021)
Near-surface geosciences																			
Engineering geology (SDG 1, 8, 9, 11)	X							X	X		X							4	Lagesse et al. (2022), Bidarmaghz et al. (2019)
Environmental geology/landscape protection (SDG 11, 13, 14, 15)											X		X	X	X			4	Wei et al. (2021), Martin (2019)
Erosion management (SDG 9, 11, 13)									X		X		X					3	Panagos and Katsoyiannis (2019) and references therein), McElwee et al. (2020), McElwee et al. (2020), Chow (2018), Schipper et al. (2021)
Minerals and rock materials																			
Mining and mineral resources (SDG 1, 2, 7, 8, 11, 12, 13)	X	X					X	X			X	X	X					7	Mudd (2021), Bendixen et al. (2021)
Critical minerals (SDG 1, 2, 7, 8, 11, 12, 13)	X	X					X	X			X	X	X					7	Toro et al. (2020), Dushyantha et al. (2020), Simandl (2014)
Battery technology (SDG 7, 11, 12, 13)							X				X	X	X					4	Paulikas et al. (2022)
Energy: extraction and storage																			
Geothermal energy (SDG 1, 7, 8, 9, 11, 12, 13)	X						X	X	X		X	X	X					7	Shortall et al. (2015), van der Zwaan and Dalla Longa (2019), Rybach (2003), Soltani et al. (2021), Bleicher and Gross (2016)
Hydropower (SDG 1, 7, 8, 9, 11, 12, 13)	X						X	X	X		X	X	X					7	Ho and Goethals (2019), Liu et al. (2013), Yuksel (2010), Shaktawat and Vadhera (2021)
Nuclear energy (SDG 1, 7, 8, 9, 11, 12, 13)	X						X	X	X		X	X	X					7	Adamantiades and Kessides (2009), Lindberg (2022), Mudd and Diesendorf (2008), Dinis and Fiúza (2021)
Renewable energy (SDG 1, 7, 8, 9, 11, 12, 13)	X						X	X	X		X	X	X					7	Ramos et al. (2021), Mehmood (2021), Schwerhoff and Sy (2017), Güney (2019)

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TABLE 1 | (*Continued*) Mapping sustainable development goals to geoscientific categories. Inspired by Gill (2017), Gill and Smith (2021) and The Geological Society (2021), updated with the categories medical geology, agrogeology, data analytics and geoheritage.

Categories	1 No poverty	2 Zero hunger	3 Good health and well being	4 Quality education	5 Gender equality	6 Clean water and sanitation	7 Affordable and clean energy	8 Decent work and economic growth	9 Industry, innovation and infrastructure	10 Reduced inequalities	11 Sustainable cities and communities	12 Responsible consumption and production	13 Climate action	14 Life below water	15 Life on land	16 Peace, justice and strong institutions	17 Partnerships for the goals	Number of matched SDGs per category	Selected references
Energy storage (gas, hydrogen, compressed air; SDG 1, 7, 8, 11, 12, 13)	X						X	X			X	X	X					6	Tarkowski and Uliasz-Misiak (2022), Tarkowski (2019), Heinemann et al. (2018), Tarkowski (2017)
Carbon capture and storage (SDG 1, 7, 11, 13)	X						X				X		X					4	Mikunda et al. (2021), De Coninck (2008), Budinis et al. (2018), Honegger et al. (2021)
Hydrocarbons (SDG 1, 7, 8, 11, 12)	X						X	X			X	X						5	Verheyen et al. (2016)
Hydrogeology and contaminant geology																			
Hydrogeology (SDG 1, 3, 5, 6, 11, 13)	X		X		X	X					X		X					6	Velis et al. (2017), Sheffield et al. (2018), Dzikunoo et al. (2020), Aggarwal et al. (2020)
Geological disposal of radioactive waste (SDG 7, 9, 11)							X		X		X							3	Themann and Brunnengräber (2021), Kim et al. (2011)
Contaminated land (SDG 1, 3, 6, 11, 13, 14, 15)	X		X			X					X		X	X	X			7	Fatimah et al. (2020)
Environmental geochemistry (SDG 1, 3, 6, 11, 13, 14, 15)	X		X			X					X		X	X	X			7	Alexakis (2021)
Climate change																			
Glaciology (SDG 11, 13, 14, 15)											X		X	X	X			4	Harrison et al. (2021)
Paleoclimatology (SDG 11, 13, 14, 15)											X		X	X	X			4	Pimentel and Kalyanaraman (2021), Varotsos et al. (2020), Trouet and Van Oldenborgh (2013)
Paleontology (SDG 13, 14, 15)													X	X	X			3	Davies and Simmons (2020)
Geoheritage, geotourism and outreach																			
Science outreach and communication (SDG 4, 5, 7, 10, 13, 14, 15)				X	X		X			X			X	X	X			7	Stewart and Hurth (2021)
Museum curation (SDG 4, 5, 7, 10, 13, 14, 15)				X	X		X			X			X	X	X			7	Nakrem et al. (2023), Lanzinger and Garlandini (2019)
Geoheritage and geotourism (SDG 4, 13, 14, 15)				X									X	X	X			4	Gordon (2019), Martínez-Frías et al. (2017), Catana and Brilha (2020)
Higher education and research																			
Geoscience research (SDG 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	17	All references in **Table 1**
Geoscience teaching (SDG 1, 4, 5, 13)	X			X	X								X					4	Avelar et al. (2019), Annan-Diab and Molinari (2017), Mehmood (2021), Pálsdóttir and Jóhannsdóttir (2021), Pimentel and Kalyanaraman (2021), Almazroa et al. (2022)

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TABLE 1 | (*Continued*) Mapping sustainable development goals to geoscientific categories. Inspired by Gill (2017), Gill and Smith (2021) and The Geological Society (2021), updated with the categories medical geology, agrogeology, data analytics and geoheritage.

Categories	**Sustainable development goals (SDGs)**																		**Selected references**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**		
	No poverty	**Zero hunger**	**Good health and well being**	**Quality education**	**Gender equality**	**Clean water and sanitation**	**Affordable and clean energy**	**Decent work and economic growth**	**Industry, innovation and infrastructure**	**Reduced inequalities**	**Sustainable cities and communities**	**Responsible consumption and production**	**Climate action**	**Life below water**	**Life on land**	**Peace, justice and strong institutions**	**Partnerships for the goals**	**Number of matched SDGs per category**	
Geoheritage and geotourism (SDG 4, 13, 14, 15)				X									X	X	X			4	Catana and Brilha (2020), Gordon (2019), Martínez-Frías et al. (2017)
Data and skill sets																			
Geophysics (SDG 6, 9, 11)						X			X		X							3	Capello et al. (2021)
GIS and remote sensing (SDG 1, 9, 13, 14, 15)	X								X				X	X	X			5	Aggarwal et al. (2020), Pirasteh et al. (2019)
Data science and analytics (SDG 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	17	Cheng et al. (2020); Sudmanns et al. (2023), Guo et al. (2020)
Innovation and frontier exploration																			
Oceanography (SDG 13, 14)													X	X				2	Nitsche et al. (2007), Ryabinin et al. (2019)
Planetary geology (SDG 9)									X									1	LI et al. (2019), Naß and Gasselt (2014)
Social geology/human-environment interaction																			
Non-governmental organisations (SDG 1, 3, 6, 9, 14, 15, 16, 17)	X		X			X			X					X	X	X	X	8	Wagaba et al. (2023), Petterson (2019)
Science policy (SDG 1, 3, 6, 9, 14, 15, 16, 17)	X		X			X			X					X	X	X	X	8	Schrodt et al. (2019)
Agrogeology (SDG 1, 2, 3, 6, 14, 15)	X	X	X			X								X	X			6	Van Straaten (2006), McElwee et al. (2020), Keesstra et al. (2016), Capron et al. (2020)
Medical geology (SDG 3, 6)			X			X												2	Bundschuh et al. (2017)
Number of categories	22	4	8	6	6	9	15	11	18	4	26	11	27	16	15	4	4		

The order and sub-grouping of the categories is identical to the article.

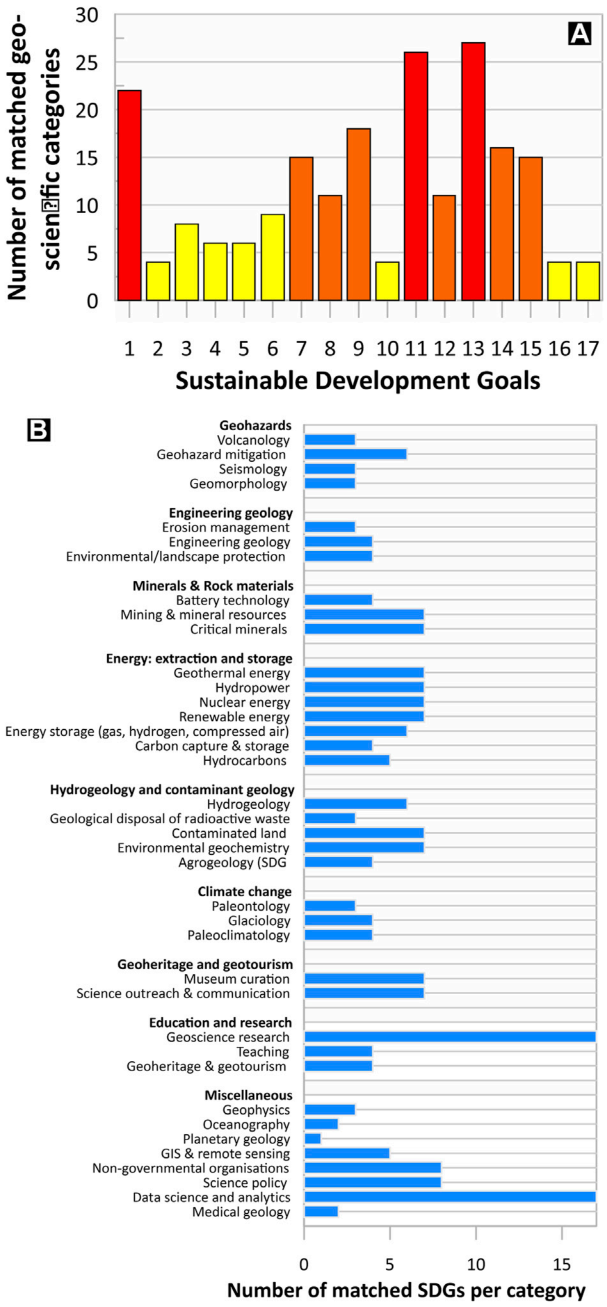

FIGURE 3 | First-order comparison of the SDGs and main geoscientific categories. **(A)** Number of geoscientific categories matched to the 17 SDGs. **(B)** List of geoscientific categories with number of SDGs matched by each category. Further details are available in **Table 1**.

and practice. The 6 February 2023 magnitude 7.8 earthquake that affected southern Turkey and northern Syria was the largest earthquake in the region for 80 years and the fifth deadliest earthquake of the 21st century (Dal Zilio and Ampuero, 2023). Satellite imagery of night lights in the area following the disaster provide a good correlation with the sustained damage (Levin, 2023).

Saunders and Becker (2015) investigate resilient and sustainable land use planning following the Darfield (magnitude 7.1; 4 September 2010) and Christchurch (magnitude 6.3; 22 February 2011) earthquakes in New Zealand. Resilient communities should also be sustainable, and the recovery period from such earthquakes demonstrates that such catastrophes, as tragic as they are, also allow for learnings and improved mitigations. Similarly, Calais et al. (2022) outline how citizen science rapidly developed a low-quality seismic network to better constrain the damaging aftershocks of the 14 August 2021 magnitude 7.2 earthquake in Haiti.

Seismicity has not only direct influence on the affected areas, but the damaged infrastructure also causes long-term indirect effects, for instance on the tourism industry. This is illustrated in Nepal, where tourism is the most important industry and seismicity is widespread (Min et al., 2020; Birendra et al., 2021).

Geomorphology (SDG 9, 11, 13)

Geomorphology, the study of the outer surface of the earth's crust, is directly linked to SDGs 9, 11 and 13 (**Table 1**; **Figure 2**).

One of the obvious contributions that geomorphologists make to the SDGs is through understanding and mitigating geohazards. Chelli et al. (2021) provide a special volume with numerous case studies on how geomorphological mapping is used to create hazard maps from various hazards, including flooding, volcanic eruptions, onshore and offshore landslides, rockfall and seismicity. De Beni et al. (2021), for instance, present ten time-lapse photogrammetric surveys using UAVs to characterize the 30 May–6 June 2019 eruption of Mt Etna. Cignetti et al. (2021) investigate rock fall in the heavily human-modified region of the Aosta Valley in northwestern Italy, by studying rockfall databases and thematic maps to create susceptibility maps.

Near-Surface Geosciences

Engineering geology is a major discipline that has employed geoscientists for centuries to build infrastructure (roads, railways, canals, artificial islands, etc.), mitigate against hazards and, in recent years, prepare for and mitigate climate change. Much of the engineering work is conducted on surface or in the near-surface (i.e., <500 m depth). To optimize engineering projects and avoid budget and time overruns, geoscientists must characterize the geological development and subsurface heterogeneities, as nicely illustrated by Shilston (2023) during his 21st Glossop Lecture.

Engineering Geology (SDG 1, 8, 9, 11)

Engineering geology is, arguably, the most society-linked branch of geology and unsurprisingly linked to a number of SDGs, notably 1, 8, 9 and 11 (**Table 1**; **Figure 2**). Lagesse et al. (2022) reviews to what extent engineering geologists already contribute to sustainable development (**Figure 6**), and outline where further contribution is possible.

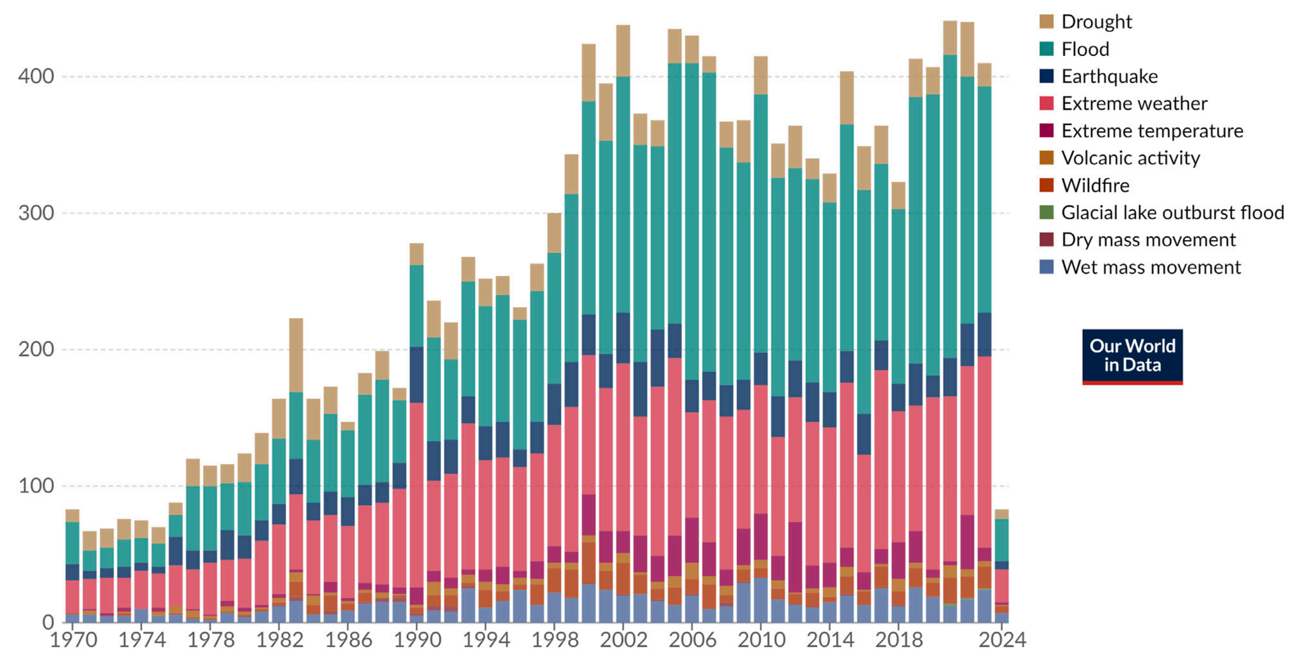

FIGURE 4 | Global reported natural disasters from 1970 to 2024 (to April), sorted by hazard type. Both weather and non-weather related disasters are included. Underlying data source: EMDAT (2024): OFDA/CRED International Disaster Database (https://www.emdat.be/). Adapted from Our World in Data, Natural Disasters, licensed under CC BY 4.0.

Key examples of contributions include development of ground models, supporting the design, construction and operation of sustainable and resilient infrastructure and enhancing construction productivity by better understanding of the ground conditions (**Figure 6**; Lagesse et al., 2022).

As more and more people move to urban areas globally, the utilization of the shallow subsurface for infrastructure (e.g., basements, road/rail tunnels, water/gas/sewage pipes, electricity/communication cables) needs to be optimized. One particular proof-of-concept study is provided by Bidarmaghz et al. (2019) who investigate how hydro(geology) influences the subsurface thermal structure in the presence of heated basements.

Environmental Geology/Landscape Protection (SDG 11, 13, 14, 15)

Environmental geology and landscape protection directly target SDGs 11, 13, 14 and 15 (**Table 1**; **Figure 2**).

A large part of this connection relates to the use of satellite data, for instance in the monitoring of wildfires (Wei et al., 2021). Martin (2019) points out that the SDGs do not explicitly mention fire, even though vegetation fires affect 3%–4% of the Earth surface each year. Fires have both negative (loss of life and property, soil desertification and contribution to climate change) and positive (e.g., land availability, nutrient release) effects on the ecosystem. As such, they directly link to SDGs 1, 2, 3, 6, 13, 14 and 15 (Martin, 2019).

Landscape protection in some locations also links to efforts in geoconversation (e.g., Gordon et al., 2021), with geoheritage parks and geotourism addressed below. Attard (2019) uses the example of the Maltese Islands to highlight the value of landscapes and landforms also in the long-term, for future generations. Furthermore, longer-term landscape protection directly influences some of the SDGs (Attard, 2019).

Erosion Management (SDG 9, 11, 13)

Managing erosion, from both mountains, rivers, and coastlines, is intricately tied to SDGs 9, 11 and 13 (**Table 1**; **Figure 2**).

Schipper et al. (2021) specifically investigate how the coastal development can be made climate-resilient and adaptable in the context of the SDGs. The work's primary objective was to tailor the SDG framework to specifically address coastal flood protection management, and illustrate these with five case studies on geologically variable coastlines around the world (Schipper et al., 2021). Also in the coastline environment, Chow (2018) investigate how mangrove plantations on Bangladesh' coastlines reduce damage by enhancing coastline stability and protecting coastal settlements during storm surges.

On a different scale, Panagos and Katsoyiannis (2019) present a special issue on soil erosion modelling, with a focus on the policy development in Europe. Soil resources are fundamental for sustainable development and thus explicitly considered in the SDGs–with a goal of zero land degradation by 2030 targeted (Keesstra et al., 2016). However, in Europe significant quantities of soil are at risk of erosion as monitored by the EU's targeted indicator system (Panagos and Katsoyiannis, 2019). The special volume led by Panagos and Katsoyiannis (2019) includes contributions on various aspects of soil erosion modelling, including the use of radiogenic soil

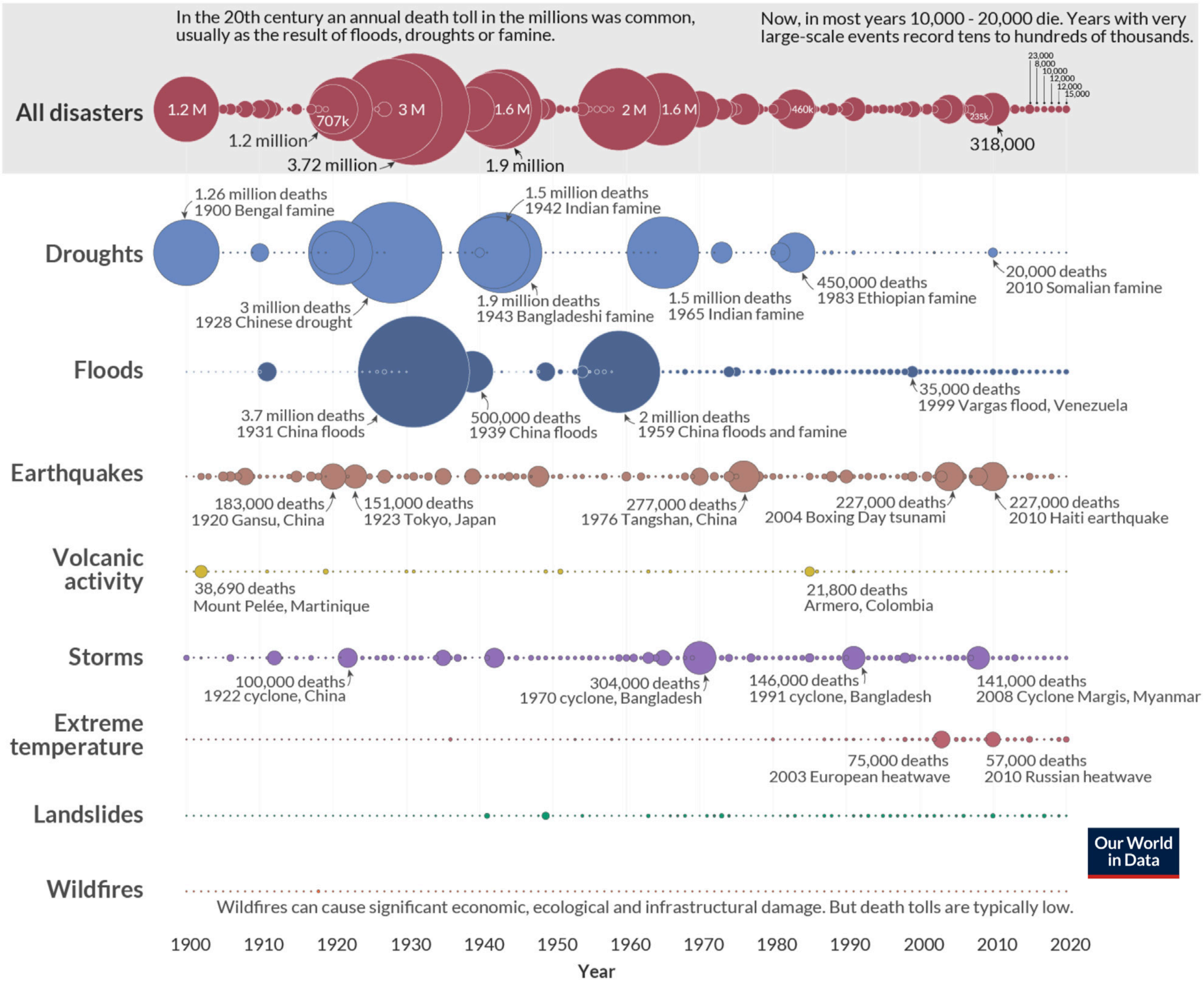

FIGURE 5 | Timeline illustrating global deaths from disasters from 1900 to 2020. The size of the bubbles represents the estimated annual death toll. Underlying data source: EMDAT (2020): OFDA/CRED International Disaster Database (https://www.emdat.be/). Reproduced from Our World in Data, Century disaster deaths, licensed under CC BY 4.0.

erosion tracers (Meusburger et al., 2018), soil recovery after wildfires (Fernández and Vega, 2018) and an integrated study of physical-geographic factors (amongst others terrain conditions and climatic parameters) to calculate total soil degradation (Bednář and Šarapatka, 2018).

Within Earth's interlocking and integrated system, any changes to the soil will also lead to effects on the food production sector. McElwee et al. (2020) reviews some of these interlinks by examining 40 different management options to see how these influence the SDGs and the Nature's Contribution to People (NCPs), amongst others to quantify the trade-offs and benefits of the options. In conclusion, there exist an ample toolbox of managing food production sustainably with limited trade-offs to SDGs and NCPs but some interventions like bioenergy and afforestation show significant negative impacts (McElwee et al., 2020).

Minerals and Rock Materials

Society is now relying on more and more minerals for its needs (**Figure 7**), particularly in the energy transition to renewables and exponential usage of electronics.

Mining and Mineral Resources (SDG 1, 2, 7, 8, 11, 12, 13)

The mining industry has long been a major recruiter of geoscientists and a contributor of minerals to the society, and is directly tied to SDGs 1, 2, 7, 8, 11, 12 and 13 (**Table 1**; **Figure 2**). Mining encompasses everything from large-scale open pit mines, to technologically advanced offshore mining to small-scale pits where aggregates (i.e., sand, gravel and crushed stone) are sourced for local usage (Bendixen et al., 2021).

There has traditionally been a perception that mining is unsustainable, often visually expressed by images of large

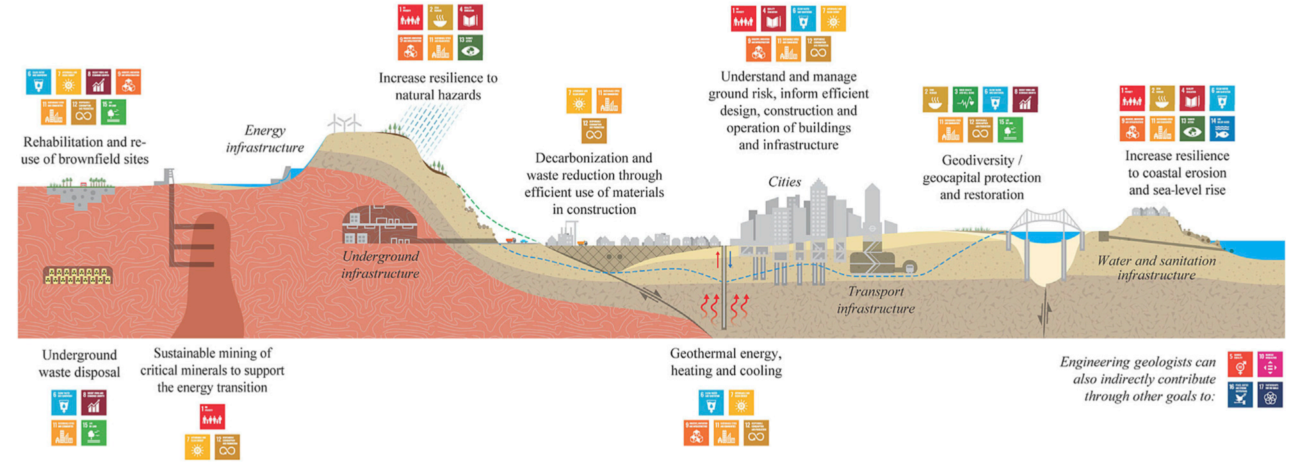

FIGURE 6 | Conceptual diagram mapping engineering geology to the SDGs. Reproduced from Lagesse et al. (2022), licensed under CC BY 4.0.

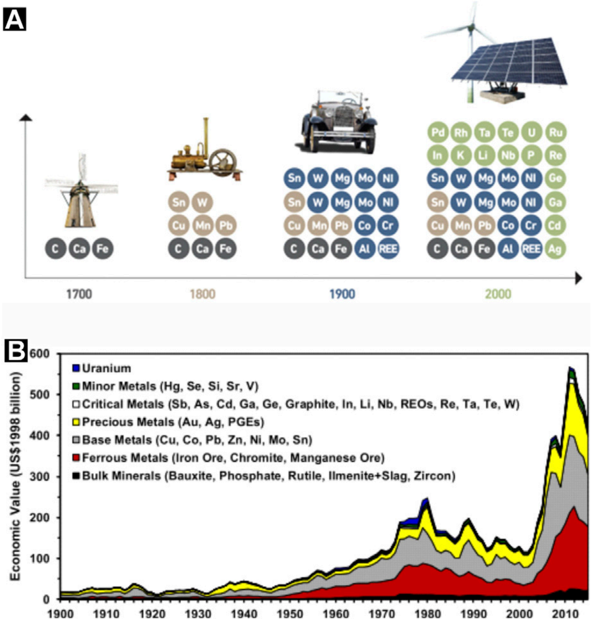

FIGURE 7 | (A) Temporal shift in the usage of minerals by society, Reproduced from Smelror et al. (2020) licenced under CC BY 4.0. Note that society today uses a lot more minerals than in the past. Source: https://www.ngu.no/nyheter/rapport-det-gr-nne-skiftet. **(B)** Real value in US$1998 of global metal and mineral production grouped by major sectors from source 1900 to 2015. Reproduced from Mudd (2021).

open-pit mines, child labor and immense mine tailings. The past decades, however, have seen a radical shift in incorporating environmental and socio-economic sustainability in mining (**Figure 8**; Mudd, 2021). Mining companies now regularly map the SDGs to their activity (**Figure 8B**) and realize the pressure from investors that mining activities should be sustainable and with minimal harm to both people and environment.

FIGURE 8 | Potential relationships between mining and the Sustainable Development Goals. Mapping mining to the SDGs by the Columbia Center on Sustainable Investment. Adapted from (CCSI, 2016), licensed under CC BY-SA 3.0.

Mudd (2021) outlines how mining relates to the SDGs and provides some key trends in mining. These involve, amongst others, an exponential increase in mined mineral resources to keep pace with the growing demand and a transition to lower grade material as the high-grade resources are produced. Together with the larger project scales, increasing mine wastes and greater demand on water and energy, the environmental burden of mining increases per ton of mined material (Mudd, 2021). Geoscientists will still contribute to frontier exploration but need to also be involved in maximizing the mineral production from existing

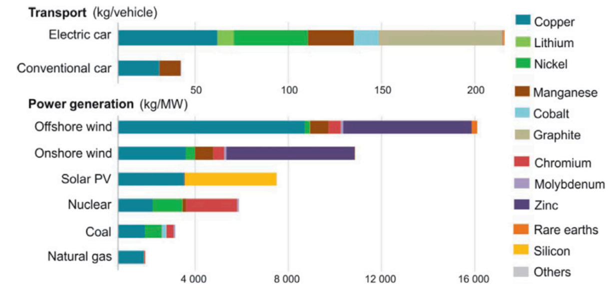

FIGURE 9 | Minerals required in the transport and power generation sectors, including selected green energy technologies, nuclear energy and fossil fuels. Figure adapted from The Nordic supply potential of critical metals and minerals for a Green Energy Transition, Eilu et al. (2022) licensed under CC BY 4.0.

mine operations. Another key aspect of mineral operations is the development and adherence of policies and frameworks that support responsible and sustainable mining. The recognition of "conflict minerals" that directly or indirectly fund wars led to the Kimberley Process that allows the certification of "conflict-free" diamonds (Mudd, 2021).

Critical Minerals (SDG 1, 2, 7, 8, 11, 12, 13)

An important group of the minerals and rock materials are critical minerals, directly linked to SDGs 1, 2, 7, 8, 11, 12 and 13 (**Table 1**; **Figure 2**). These are classified by the International Energy Agency (IEA) as "essential components in many of the rapidly growing clean energy technologies" and include minerals such as copper, lithium, nickel, cobalt, and rare earth elements (**Figure 9**).

The global distribution of critical minerals is heterogeneous, controlled by geology. Rare earth elements (REEs) are, for instance, typically produced from carbonatite-related deposits and ion absorption clays (Simandl, 2014; Dushyantha et al., 2020). Other REE exploration targets include peralkaline igneous rocks, pegmatites, monazite ± apatite veins, ion adsorption clays, placer deposits and some deep sea deposits (Simandl, 2014). China produces >90% of the global REE requirement (Dushyantha et al., 2020). REEs are not just critical ingredients for the energy transition, they are also strategic minerals from economic, environmental, and national security perspectives.

Unsurprisingly, then, regional efforts are underway to explore for and sustainably develop such critical resources. One of these efforts is the EU-funded Greenpeg project, outlined by Müller et al. (2022), which aims to develop multimethod exploration toolsets to identify pegmatite ore deposits in Europe.

Exploring for and finding ore deposits is one thing, but sustainably extracting these is another issue. Hancock et al. (2018) discuss this in the context of extracting lithium in Bolivia using public-private-partnerships. Ali et al. (2017) point out that reaching the SDG targets will require mineral-consuming technologies and that global resource governance is crucial that these are produced sustainably.

Battery Technology (SDG 7, 11, 12, 13)

In the context of the energy transition and the electrification of road transport, sustainably sourcing materials for batteries represents a significant bottleneck in delivering to the society's targets. Battery technology is directly related to SDGs 7, 11, 12 and 13 (**Table 1**; **Figure 2**).

Not only does an electric car consume about five times more materials than a conventional car (**Figure 9**), but it also relies on more and rarer minerals, including lithium, nickel, manganese, cobalt and graphite.

The green energy revolution will require vast amounts of such critical materials (e.g., a projected demand increase of 500% for graphite, cobalt and lithium) which at present are largely sourced from onshore mining (Herrington, 2021). Additional sources for cobalt and manganese are recovery of waste material from existing mines, recycling of used batteries (Dominish et al., 2021) or deep-sea mining (Toro et al., 2020; Paulikas et al., 2022).

Deep-sea mining of critical minerals is controversial (e.g., Beaulieu et al., 2017)—with some considering it to be a major and necessary step to achieve the SDG targets, while others cautioning that the environmental risks are too high. Paulikas et al. (2022) compare the life cycles of deep-sea nodule-based extraction and traditional onshore mining, concluding that nodule-based metal production may generate waste (in terms of both volumes and severity) but uncertainty remains on the environmental effects on the disrupted sediments. The recent controversial opening for deep-sea licensing rounds in the Norwegian sector of the North Atlantic mid-ocean ridge will contribute to new knowledge and data on the deposits and environmental issues related to possible deep-sea mining.

Irrespective of where the minerals are sourced, making full use of existing resources and optimizing energy systems is vital to provide the end users with clean yet affordable energy (i.e., SDG7). Kyriakopoulos and Arabatzis (2016) review some of the complexities of energy storage systems in electricity generation, providing case studies of emerging technologies that may facilitate a sustainable future. Of most relevance, for geoscientists, are compressed air energy storage systems making use of subsurface aquifers for energy storage.

Energy: Extraction and Storage

The energy sector also employs many geoscientists, in exploration, production and in recent years also increasingly in the energy storage and renewable energy sectors. Geoscientists are also important contributors in the energy transition, with for instance near-surface subsurface mapping for onshore and offshore wind parks. The energy sector SDG 7 is inter-linked, both positively and negatively, to non-energy SDGs (McCollum et al., 2018).

Geothermal Energy (SDG 1, 7, 8, 9, 11, 12, 13)

Geothermal energy is directly relevant to SDGs 1, 7, 8, 9, 11, 12 and 13 (**Table 1**; **Figure 2**).

Geothermal energy is expected to exponentially grow and contribute with power production of 800–1300 TWh/yr by 2050 (van der Zwaan and Dalla Longa, 2019). By 2050 geothermal energy may contribute 2%–3% of the global electricity generation (van der Zwaan and Dalla Longa, 2019). For comparison, the global power generation capacity from geothermal installations in 2021 accounted for 15,854 MWe (ThinkGeoenergy, 2022). Given that geothermal energy shares much of the technology and skill sets of the oil and gas sector, there is a strong interest in geothermal energy in the context of decarbonization and energy transition.

Rybach (2003) outlines geothermal resources in terms of sustainability and renewability, highlighting that environmental effects of geothermal energy are minor and controllable. Some of the most sever effects include enhanced seismicity during the injection phase, which has led to some geothermal projects needing to be stopped. Shortall et al. (2015) review the linkages between sustainability and geothermal-derived electricity generation. The main conclusions suggest that customized assessment frameworks are necessary to define reliable sustainability indicators–ideally with the involvement of stakeholders in several countries (Shortall et al., 2015).

While only deep geothermal systems in areas of significant heat flow can contribute to electricity, shallow to medium depth geothermal systems for district heating are also important components in energy efficiency and lower CO_2 emissions. Geothermal heat pumps at the household level, for instance, are considered an excellent energy source for heating homes with minimal environmental impact. However, as pointed out by Bleicher and Gross (2016), geothermal technology is much more interlinked with the complex environmental system of the subsurface than other energy carriers, and care must be taken to account for these to reduce development risks.

Hydropower (SDG 1, 7, 8, 9, 11, 12, 13)

Society has for centuries harvested power from rivers to generate electricity, linking to SDGs 1, 7, 8, 9, 11, 12 and 13 (**Table 1**; **Figure 2**).

In some mountainous countries like Norway, Switzerland, Austria or New Zealand, hydroelectric power already contributes most of the domestic energy production. In other countries, such as China (Liu et al., 2013) or Turkey (Yuksel, 2010) hydroelectric power is gaining in importance and capacities are growing.

Geologists and geological engineers are involved in optimizing the locations of dams and in ensuring their safe and sustainable operations. Hydropower projects are typically large and complex, with significant economic, environmental and social implications and significant uncertainties and risks during their development. Shaktawat and Vadhera (2021) review some of these risks, focusing on sustainable development incorporated within the risk management of hydropower projects.

Liu et al. (2013) provide a case study of the world's largest hydropower project, the Three Gorges Project in China, that was completed in 2009. The focus is on how sustainability was considered during the project development stage, but also mentions some of the negative effects, notably forced resettlement and environmental issues.

We should not forget that man-made hydropower reservoirs are, just as other inland lakes, an important source of fresh water. And this reservoir is increasingly under pressure through both local and global issues, including eutrophication and loss of biodiversity (Ho and Goethals, 2019). Ho and Goethals (2019) investigate some of these factors considering the SDGs, proposing 22 indicators to monitor the health of inland lakes and reservoirs in the future.

Nuclear Energy (SDG1, 7, 8, 9, 11, 12, 13)

Nuclear energy is arguably the most controversial energy source, with the benefit of low carbon intensity with limited fuel requirements offsetting perceived risks and the dilemma of long-term storage of radioactive waste. Nuclear energy is directly linked to SDGs 1, 7, 8, 9, 11, 12 and 13 (**Table 1**; **Figure 2**).

y Leòn and Lindberg (2022) make a strong case for nuclear energy in terms of the SDGs, highlighting how nuclear energy may contribute to virtually all the SDGs but primarily to SDG7 (Affordable and Clean Energy). The reasoning is that nuclear energy can be deployed in low and middle income countries at an acceptable cost with little CO_2 emissions to essentially jump over the carbon-intensive development many high income countries have experienced through the oil age (y Leòn and Lindberg, 2022).

Geologists contribute both to the exploration and mining of the nuclear fuel uranium, and to the safe long-term storage of radioactive waste. Mudd and Diesendorf (2008) investigate the sustainability of uranium mining and provide an overview of global uranium production and associated demands on energy and water. As with other minerals, uranium ore grades are likely to gradually decline during the next decades, leading to increased water and energy demands and likely decreasing the sustainability of uranium mine operations (Mudd and Diesendorf, 2008).

Dinis and Fiúza (2021) review uranium mining remediation, with a focus on groundwater contamination and the mitigating technologies. The key message is that the most effective remediation technologies will be site-specific, incorporating both the site-specific geology and the technological treatments available.

The storage of radioactive nuclear waste is covered separately below.

Renewable Energy (SDG 1, 7, 8, 9, 11, 12, 13)

Renewable energies with low carbon intensity are the target, but so far (in 2019) they only contributed, together with nuclear energy, with 16% to the global energy mix (Ritchie and Roser, 2020). Nonetheless they represent an important target for the SDGs by 2030, and directly relate to SDGs 1, 7, 8, 9, 11, 12 and 13 (**Table 1**; **Figure 2**).

Güney (2019) conducted a global study (with 40 developed and 73 developing countries) to judge the impact of countries relying on renewable and non-renewable energy on their sustainable development. The method implements adjusted net savings as a proxy for sustainable development and concludes that switching to renewable energy will, as expected, lead to more sustainability.

Site-specific surveys were also published–for instance the review of Sen et al. (2016) covering all renewable energies in India, highlighting both challenges and opportunities for development. The authors also consider the macro-economic and geopolitical benefits of home-produced renewable energy but also note that for net fossil fuel importers like India it is still the cost of oil that determines whether renewables are viable or too expensive alternatives.

The issue of financing the energy transition in developing countries is also highlighted by Schwerhoff and Sy (2017) in the context of Africa. Renewable energies are seen as an important investment step from a social point of view. The monetary cost, however, is hampered by the still too high economic cost and low credit ranking of many African countries. A plausible solution is the increase of investment from international funding (Schwerhoff and Sy, 2017).

Geoscientists already play a strong role in sourcing material necessary for the renewable revolution (see section on critical minerals above). But they also contribute in near-surface studies, for instance the foundation of wind parks. This is particularly true in offshore settings, where similar site surveys as conducted for drilling hydrocarbon boreholes are undertaken. The bigger obstacles for marine renewable energy projects (including both offshore wind farms but also exploitation of waves, tides and ocean currents) are, as outlined by Ramos et al. (2021) using the Atlantic region of Europe as a case study, not technical but regulatory, related for instance to licensing procedures.

Energy Storage (Gas, Hydrogen, Compressed Air; SDG 1, 7, 8, 11, 12, 13)

Contrary to traditional fossil fuels and nuclear energy, renewable energies often produce electricity on an irregular basis with implications on seasonal variation and grid infrastructure. The storage of energy in the subsurface will thus increase steadily in the future and energy storage is linked to SDGs 1, 7, 8, 11, 12 and 13 (**Table 1**; **Figure 2**).

There already are 642 underground gas storage sites operating globally (Tarkowski, 2019). They are comparatively cheaper per unit volume than corresponding storage tanks on the surface, take less space on the ground and are more resilient to wildfires, terrorist attacks and other catastrophes. These are usually filled with natural gas in the summer months when demand is low, with gas produced and transported to the customers in the winter months.

In recent years, the role of hydrogen in the energy transition has increased and is projected to become the dominant fuel for the 21st century (**Figure 10A**). Hydrogen is being hailed as the future fuel applicable in many carbon-intensive sectors including industry, transportation, heating and power generation. Indeed, hydrogen only produces oxygen when burned and is a colourless gas. The various colours assigned to hydrogen, blue, green, grey, etc., reflect solely the mechanisms and carbon intensity of hydrogen production. Green hydrogen is the only type produced in a climate-neutral manner, with energy from renewable energies fueling the pyrolysis process. Hydrogen can also be generated through steam reforming using fossil fuels, producing CO_2 and carbon monoxide in the process. If these byproducts are not re-captured the resulting hydrogen is "grey," if the byproducts are captured and stored underground the hydrogen is "blue."

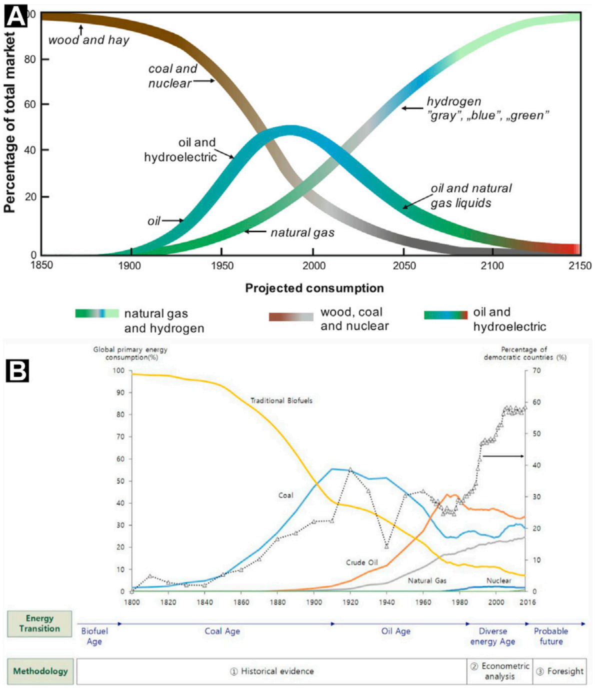

FIGURE 10 | Global energy mix development. **(A)** Global energy consumption from 1850, with projection to 2150. R. Tarkowksi et al., 2022, reprinted with permission from Elsevier. **(B)** Timeline illustrating the main stages of the energy transition from 1800 to 2016., along with the global uptake of democracy. Lee et al., 2019, reprinted with permission from Elsevier.

Once produced, hydrogen can, as methane or carbon dioxide (CO_2), be stored in geological aquifers and produced when needed. Tarkowski (2019) presents various hydrogen subsurface solutions, including porous rocks (saline aquifers and depleted hydrocarbon fields) and artificial underground cavers (salt caverns, disused mine shafts). Hydrogen has already been stored in three salt caverns in Teeside in the UK since 1972 and in two sites in Texas since 1983 (Tarkowski, 2019). As with CO_2 storage, reservoir and pressure conditions will determine the gas phase and density and thus influence the storage capacity. Hydrogen has stronger penetrability, lower density, lower viscosity and lower dissolution than methane, with a stronger tendency to leak (Heinemann et al., 2018; Tarkowski, 2019).

Tarkowski and Uliasz-Misiak (2022) focus on some of the barriers to industrial-scale hydrogen storage, specifically highlighting the importance of more research on site-specific rock-fluid interactions and field demonstration of hydrogen storage in saline aquifers. The identification of possible storage site follows a similar workflow as for CO_2 storage capacity assessments, with storage sites identified for instance for Poland (Tarkowski, 2017) or the UK's Midland Valley area (Heinemann et al., 2018).

Carbon Capture and Storage (SDG 1, 7, 11, 13)

Carbon capture and storage (i.e., CCS) is one of the geoengineering mitigation measures that the IPCC includes as a critical measure to reach the Paris Agreement targets. CCS is directly linked to SDGs 1, 7, 11 and 13 (**Table 1**; **Figure 2**).

CCS involves capturing CO_2 emissions at point sources, transporting it to suitable storage sites and injecting it in porous and permeable saline aquifers for permanent storage. The method is technically feasible and mature, with Norwegian oil company Equinor having injected ca. 1 mill tons of CO_2/year at Sleipner field in the North Sea since 1996 (Eiken et al., 2011) and currently operating the Northern Lights full-scale CCS project (Furre et al., 2019). The biggest obstacles relate to public perception, especially in onshore sites (L'Orange Seigo et al., 2014), and the sheer scale of CCS projects needed to achieve the global targets specified by the IPCC (Budinis et al., 2018; English and English, 2022; Ma et al., 2022). Global storage capacity estimates suggest that there are between 8,000 and 55,000 gigatonnes (Gt) practically accessible storage capacity available (e.g., Kearns et al., 2017). The challenge is to link these storage sinks to industrial point sources and speed injection up to Gt annual injection rates. Recent industrial developments, such as a planned industry-operated CO_2 pipeline linking point sources in Germany with storage sites in the offshore Norwegian North Sea and the Greensand project storing CO_2 from Belgium in the offshore Danish North Sea, indicate that CCS is truly gaining momentum. The concept of CO_2 storage licenses in many petroleum nations like Norway and the UK are in parallel strongly relying on geoscientists' subsurface skills.

While technically feasible, CCS is far from being fully accepted by the public. Even before the SDGs came into existence, De Coninck (2008) outlined the polarized discussion on including CCS in the Kyoto Protocol's Clean Development Mechanism. The past decades, including the ever-important industrial test sites with monitoring programs highlighting the storage integrity, have partly closed this deep divide.

Indeed, Mikunda et al. (2021) critically reviews CCS specifically in terms of the SDGs, highlighting all project stages including capture and transportation technologies. CCS shows many enabling mechanisms for the SDGs with the only inhibiting mechanism related to higher energy need per unit electricity and environmental issues associated with some of the capture facilities (Mikunda et al., 2021). Overall, however, CCS is a sustainable option to combat climate change. The findings are consistent with the broader study of Honegger et al. (2021) who in addition to CCS also investigate the broader range of carbon removal solutions, including direct air capture.

Hydrocarbons (SDG 1, 7, 8, 11, 12)

Many geoscientists are intricately involved in the exploration and production of fossil fuels, thereby contributing to SDGs 1, 7, 8, 11 and 12 (**Table 1**; **Figure 2**). In 2019, the fossil fuels oil, gas and coal contributed 84.3% (down from 86.1% in 2000) to the global primary energy consumption (Ritchie et al., 2022) and with a projected rise in demand due to population growth and increase in the quality of life fossil fuels will contribute to the energy mix for many decades to come.

The coal age, and subsequently the oil age (**Figure 10B**) largely shaped the earth as we know it today, and the living quality we take for granted. The coal age powered the industrial revolution, while the oil age was responsible for globalization and re-defining the transport and industrial sectors. The challenge is that the resource extraction of these non-renewable (at least on the societal timescales) resources has more often than not been poorly managed, resulting in unsustainable production and many negative effects on both societies (e.g., corruption, conflicts) and the landscape (e.g., oil spills, blowouts, destruction of landscapes) are documented, for instance in Africa's Great Lakes (Verheyen et al., 2016).

Even in the phase of energy transition and diversification, hydrocarbons will continue to the energy mix for many decades. In this context it is important to highlight the attitude transition of oil companies who acknowledge the challenges of continuing fossil fuel production by outlining often ambitious sustainability plans linked to the SDGs (Equinor, 2021). Oil companies have several pathways to produce the same (or increasing) volume of hydrocarbons, for instance by decarbonization its activities through reducing greenhouse gas (GHG) emissions throughout the value chain by CCS and other tools. Obviously measures will be different around the world, with Dmitrieva and Romasheva (2020) highlighting the need for technological advances to produce hydrocarbons in the Russian Arctic.

Hydrogeology and Contaminant Geology

Exploration for and access to fresh water will always represent one of society's greatest needs. The complex coupling of surface water, groundwater and anthropogenic contaminants is also vital, and requires geoscientific involvement.

Hydrogeology (SDG 1, 3, 5, 6, 11, 13)

Exploration for groundwater and facilitating its access is directly linked to SDGs 1, 3, 5, 6, 11 and 13 (**Table 1**; **Figure 2**).

Water is intricately linked to several SDGs and its unsustainable exploitation in many cases results in local to regional-scale issues as illustrated in **Figure 11**. The concept of socio-hydrology, explored by Di Baldassarre et al. (2019) specifically in the context of the SDGs, addresses the complex interactions of the water and human systems at both short and longer time scales.

Groundwater accounts for 98% of the global fresh water and represents the primary drinking water supply for half of the world's population (Kløve et al., 2011). Velis et al. (2017) critically review the synergies and trade-offs between human

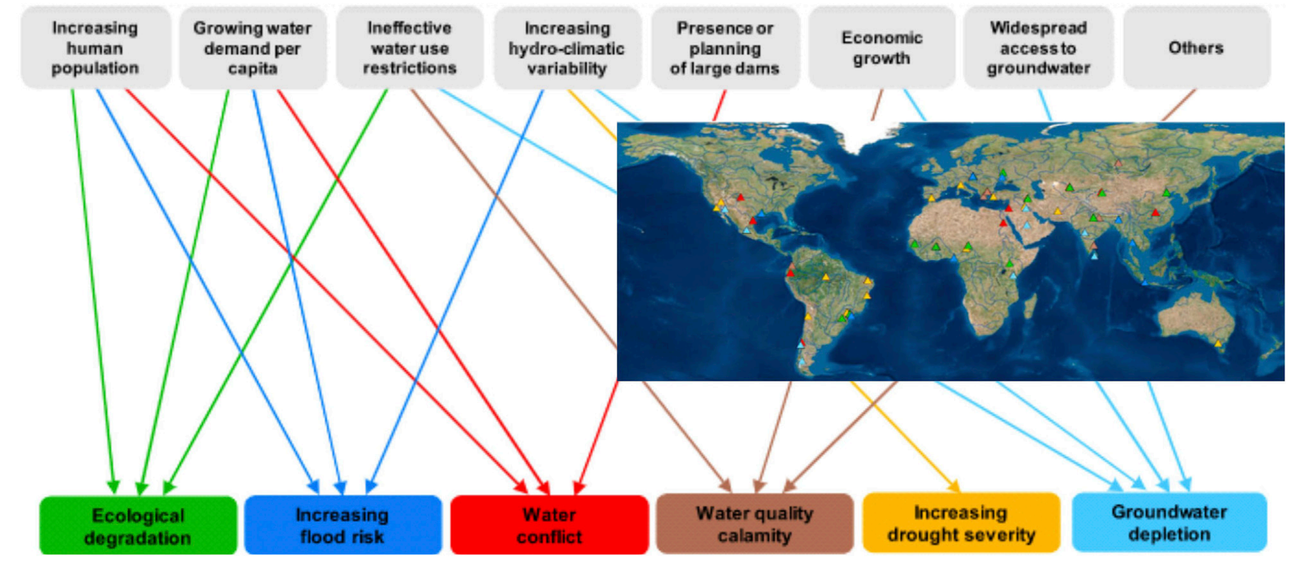

FIGURE 11 | Overview of the social, technical and hydrological factors that influence the six major water crises. The inset map shows the location of global hot spots of water crises. Reproduced from Di Baldassarre et al. (2019), licensed under CC BY 4.0.

and groundwater development. Groundwater enhances food security through irrigation of nutritious crops, improves access to drinking and sanitation water, has a major role to play in the energy transition as a buffer system and can be used to adapt to ongoing climate change (Velis et al., 2017). However, human development can also lead to reduction in groundwater quality and quantity. Groundwater aquifers are heterogeneous, with reservoir properties (e.g., porosity, permeability, thickness) and recharge potential (e.g., overburden lithologies, depth, recharge pathways and climatic conditions) determining if a particular reservoir is prone to depletion or quality deterioration over time (Velis et al., 2017).

Managing water resources, both groundwater and surface water, requires both sustainable policies and well-designed monitoring systems to provide adequate data on critical parameters like drinking water access and water-related geohazards (e.g., droughts, floods) to the authorities. This is especially problematic in data-poor regions such as many developing countries, but may in some cases be addressed through the use of remote sensing data from satellites. Sheffield et al. (2018) consider both current data and planned missions in the context of water resource management, arguing that remote sensing is largely underutilized. Such data are in particular powerful when coupled with site-specific on-the-ground monitoring and hydrological modelling, as illustrated by Aggarwal et al. (2020) for the north-western Himalaya.

As with many subsurface applications, groundwater exploration and production are often hampered by the lack of relevant data. Re-using existing subsurface data from petroleum or ore exploration provides an opportunity to overcome some of these limitations. In this context, Dzikunoo et al. (2020) use potential field and subsurface data to build a geological model of the Nasia sub-basin in northern Ghana, where groundwater is critical for irrigation in view of erratic rainfall.

Geological Disposal of Radioactive Waste (SDG 7, 9, 11)

Nuclear energy may provide cleaner energy as discussed above, but its global uptake is hampered by the uncertainty of safe and permanent storage of radioactive waste, directly linked to SDGs 7, 9 and 11.

Since 2022 Finland operates a permanent storage for its nuclear waste at the Onkalo site (El-Showk, 2022). Remarkably, this is the first global permanent storage site after more than half a century of using nuclear energy for electricity production. Other countries' radioactive waste management strategies typically involve reprocessing the waste, temporary storage and permanent direct storage plans for the upcoming decades (Kurniawan et al., 2022).

Chapman and Hooper (2012) review the concept of underground storage of radioactive waste, outlining both the role of the geological environment, regulatory implications, and developments in the United Kingdom. The produced waste is small compared to other fossil fuels but due to its high radioactivity and continued heat emission potential difficult to store permanently. In terms of geology, there is no "best rock" to host the radioactive waste but crystalline hard rocks (e.g., granite), clay-rich sedimentary formations, evaporites and unsaturated volcanic tuffs have all been considered (Chapman and Hooper, 2012). The key property of the host rock is low fluid flow potential around the site and stable geochemistry. Furthermore, site selection must also consider post-storage geological factors such as rock deformation, seismicity, volcanicity, uplift, glacial erosion, ice loading and sea level changes, all of which can compromise the containment stability (Chapman and Hooper, 2012)

In addition to the geological factors of the storage site(s), geotechnical aspects including canisters, buffers and barriers with suitable geological materials must be considered (Kim et al., 2011).

Contaminated Land (SDG 1, 3, 6, 11, 13, 14, 15)

Contamination of land negatively influences both the ecosystems and the humans relying on it, and is linked to SDGs 1, 3, 6, 11, 13, 14 and 15 (**Table 1**; **Figure 2**). There are also strong synergies and overlaps to the agrogeology and medical geology categories discussed below.

For instance, Ruidas et al. (2024) characterize groundwater contamination with arsenic and fluoride in the Indo-Bangladesh delta region, with negative impacts on both drinking water and agricultural output found for 55% of the study area. The high seasonality between dry and wet seasons is evident when the groundwater samples are analyzed.

Contamination can be both geogenic and anthropogenic in origin. One of the obvious local sources are waste disposal sites. In this context, Fatimah et al. (2020) present an innovative waste management system for several smart cities in Indonesia, combining industry 4.0 (i.e., Internet of things) and sustainable circular economy.

Environmental Geochemistry (SDG 1, 3, 6, 11, 13, 14, 15)

Environmental geochemistry has close links to contaminated land, hydrogeology, and medical geology, and directly links to SDGs 1, 3, 6, 11, 13, 14 and 15 (**Table 1**; **Figure 2**).

In essence, environmental geochemistry deals with characterizing the near-surface through systematic baseline surveys and ideally also monitoring. Plant et al. (2001) introduces global-scale environmental geochemistry, highlighting the importance of climate (e.g., humid vs. arid) and pole-to-equator gradients in driving the major near-surface processes globally. Already in 2001 the authors argued for a consistent global environmental geochemical baseline study. Two decades later, such studies are still only available for single regions, countries, or industrial projects. Selected published examples include India (Govil et al., 2020), China (Wang et al., 2022), Papua New Guinea (Tiangang et al., 2024), a pre-mining assessment in Egypt (Mostafa et al., 2023), and a special volume reviewing continental-scale geochemical mapping projects in Austria, Europe and the United States (Smith et al., 2023).

One obvious caveat is that while environmental geochemical data acquisition should be consistent, it is heavily affected by the underlying geological regolith, weathering processes and human activity. Salminen and Gregorauskien (2000) illustrate this through a case study comparing Finland and Lithuania, where the differences in baseline elemental concentrations depend not only on differences in underlying geology, but also on the sampling strategy (e.g., grain size, extraction method).

Climate Change

Geoscientists are instrumental in providing constraints on the Earth's natural climate variability in the past and subsequently to use this knowledge to inform the society of possible effects of climate change on the various spheres. Much of this knowledge is summarized in various editions of the IPCC report (Intergovernmental Panel on Climate Change, 2021). The IPCC report states that "*Earth's climate system has evolved over many millions of years, and evidence from natural archives provides a long-term perspective on observed changes and projected changes over the coming centuries*." Importantly, the IPCC also highlights the need for adapting to ongoing climate change (Portner H. O. et al., 2022), where many of the predicted scenarios are based on the Earth System understanding based on the geological past.

Glaciology (SDG 11, 13, 14, 15)

Glaciers provide fundamental data on ongoing climate change through both past and present climate archives, provide drinking water to immense populations worldwide and, in many cases, are intricately linked to geohazards. As such, glaciology is directly linked to SDGs 11, 13, 14 and 15 (**Table 1**; **Figure 2**).

At the same time, glaciers are experiencing major changes due to ongoing climate change.

Nussbaumer et al. (2017) reviews the capacity building and global monitoring of glaciers in the framework of the Global Terrestrial Network for Glaciers (GTN-G). Such efforts are critical in terms of sustainable development especially with respect to drinking water supply in glaciated regions, for instance around the Andes (Gomez et al., 2022) or Himalayas (Sharma et al., 2021). In this context, long-term monitoring of glaciers and icecaps through remote sensing and ground observations is crucial.

Such data also contribute to glacier-related geohazards. One example is the study of a massive rock and ice avalanche from 2021 in the Indian Himalaya by Shugar et al. (2021).

Paleoclimatology (SDG 11, 13, 14, 15)

The study of past climates, paleoclimatology, is directly linked to SDGs 11, 13, 14 and 15 (**Table 1**; **Figure 2**).

Geologists have always inferred past environments from the geological record at timescales exceeding millions of years (e.g., Barghoorn, 1953; Crowley, 1983; Burke et al., 1990; Lear et al., 2021). Such studies highlight the fact that the geological record is the only record of past changes (Burke et al., 1990), and thus the only data that can be used to constrain climate models of the complex Earth system, which are crucial in providing robust predictions of how the climate will evolve in the future.

Lear et al. (2021) provides an excellent synthesis of how the geological record informs society about the present and future climate change, arguing that "*Geoscientists are making vital contributions to all of the UN's Sustainable Development Goals and that includes the human response to climate change and its impacts.*"

However, the Earth System is complex and the longer back in the past the more uncertain the paleoclimate proxies are (**Figures 12A, B**). Furthermore, interlinkages between terrestrial-marine-atmospheric processes need to be better constrained and

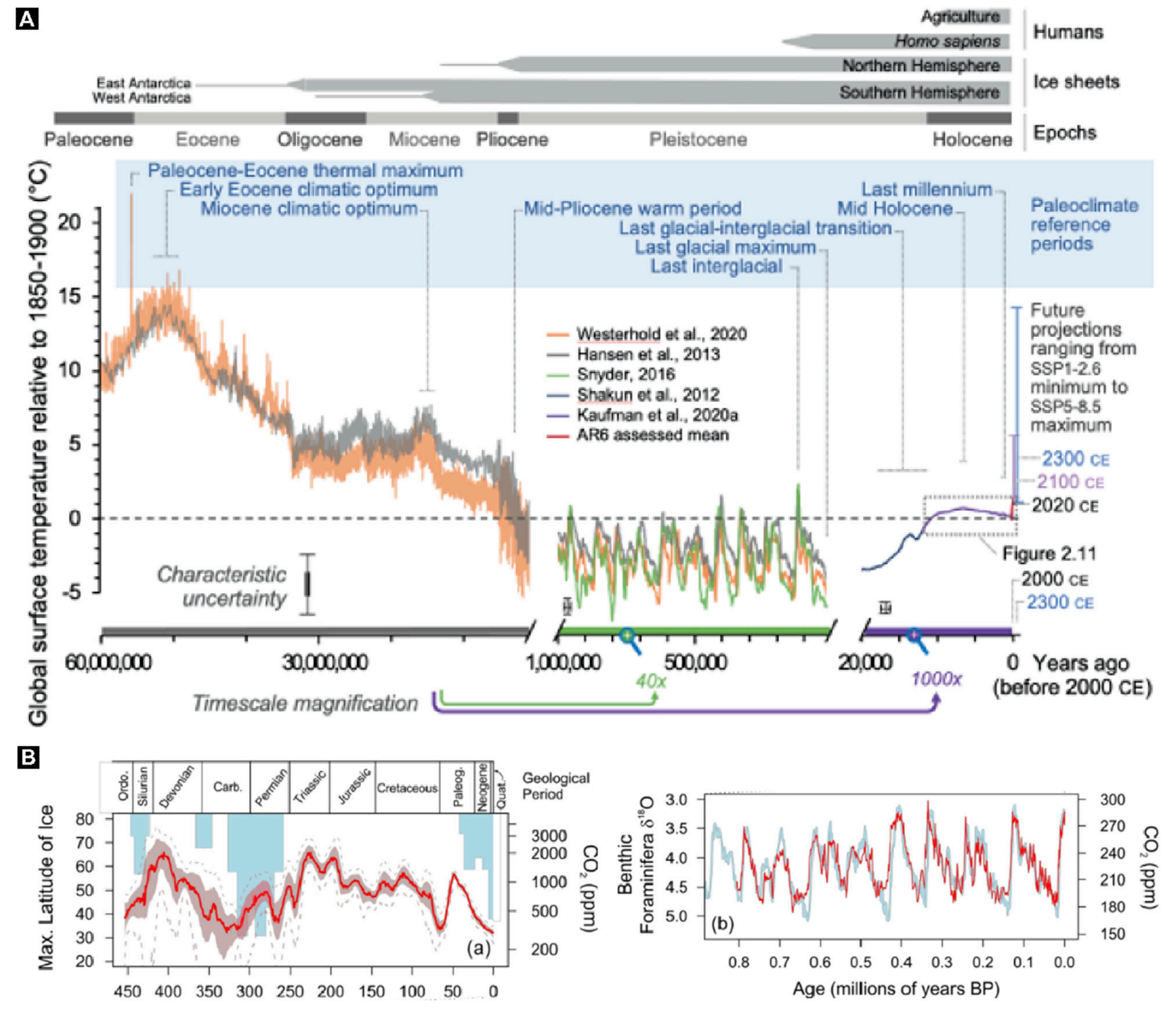

FIGURE 12 | (A) Global mean surface temperature (GMST) over the past 60 million years (60 Myr) relative to 1850–1900 shown on three time scales. Information about each of the nine paleo reference periods (blue font) and sections in AR6 that discuss these periods are listed in Cross-Chapter Box 2.1 Table 1. Grey horizontal bars at the top mark important events. Characteristic uncertainties are based on expert judgement and are representative of the approximate midpoint of their respective time scales; uncertainties decrease forward in time. GMST estimates for most paleo reference periods (Figure 2.34) overlap with this reconstruction, but take into account multiple lines of evidence. Future projections span the range of global surface air temperature best estimates for SSP1–2.6 and SSP5–8.5 scenarios described in Section 1.6. Range shown for 2100 is based on CMIP6 multi-model mean for 2081–2100 from Table 4.5; range for 2300 is based upon an emulator and taken from Table 4.9. Further details on data sources and processing are available in the chapter data table (Table 2.SM.1). Reproduced from IPCC, Changing State of the Climate System, licensed under CC BY-NC-ND 4.0. Caption from the original figure. **(B)** Global atmospheric CO_2 concentrations over the past 450 million years, with a zoom-in to the Holocene. Reproduced from Lear et al. (2021), licensed under CC BY 4.0, who also present the original data sets of the latitudinal extent of continental ice sheet deposits, atmospheric CO_2 content in the deep-time and from ice cores, and the benthic foraminiferal $\delta^{18}O$ record.

understood. Varotsos et al. (2020) investigated Holocene (past 10,000 years) records from peats in European Russia using three parameters (water table depth, peat humification and climate moisture index) to study the paleoclimate dynamics.

Crowley (2000) specifically investigates the past 1,000 years to put the post-1850 industrial revolution into a historical context, concluding that the recent temperature increase is well beyond that of natural variability.

Paleontology (SDG 13, 14, 15)

Paleontology relates to understanding the origin and evolution of life, and is linked to SDGs 13, 14 and 15 (**Table 1**; **Figure 2**).

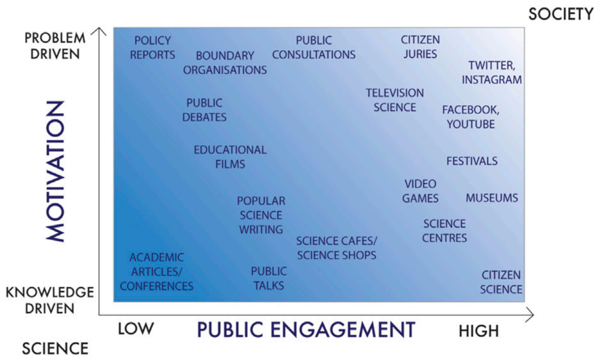

FIGURE 13 | Conceptual depiction of a landscape in science communication, reproduced from Stewart and Hurth (2021).

In terms of the UN SDGs, paleontology provides the evidence of life evolution and the diversity of the "tree of life" (Benton and Donoghue, 2006). Understanding the processes leading to both mass extinctions and diversification of life forms is crucial in a time when the Earth is undergoing some of the most rapid climate change in its history.

Davies and Simmons (2020) consider the role of stratigraphers, sedimentologists, and paleontologists in the context of the energy transition. While all of them have important skills applicable (and applied) in the energy transition (for instance in characterizing CO_2 storage reservoirs), they all have an important role to play as "*the custodians and curators of Earth History, perfectly placed to advise on the future of the planet*... ".

Geoheritage, Geotourism, and Outreach

Geoscientists are instrumental in "translating" the geological evolution of Earth, its complex processes, and the societal relevance of geology to society through innovative scientific outreach. Natural arenas for this are museums and geoheritage sites.

Science Outreach and Communication (SDG 4, 5, 7, 10, 13, 14, 15)

Communicating scientific research to a wider audience is an integral part of geoscientists' work and contributes directly to addressing SDGs 4, 5, 7, 10, 13, 14, 15 (**Table 1**; **Figure 2**).

Stewart and Hurth (2021) present an excellent reflection of the various ways through which geoscientists communicate with the public (**Figure 13**). One of their main messages, however, was that scientists need to consider techniques from marketing to exponentially enhance public engagement. Peer-reviewed scientific articles are only the beginning of efficient research, with a clear strategy, ideally involving also co-creation, is required to make a significant impact. As geoscientists, we have a crucial role in "translating" scientific knowledge to the public and policymakers, with the themes of climate change, extreme natural hazards, resource conflicts and the energy transition in particular needing geoscience communicators (Stewart and Hurth, 2021).

There are numerous examples of alternative outreach initiatives, for example, the web-based Climate Explorer application that facilitates statistical analysis of past climate (Trouet and Van Oldenborgh, 2013). Pimentel and Kalyanaraman (2021) present the "Virtual climate scientist," a virtual reality (VR) platform to digitally visit climate researchers working in Antarctica and decipher past climate from ice core records. Virtual reality, which is also increasingly used in geoscience education (Horota et al., 2022a), has the added benefit of facilitating the involvement of a broader audience group irrespective of social and economic backgrounds.

Museum Curation (SDG 4, 5, 7, 10, 13, 14, 15)

Curators and other staff at natural history museums worldwide contribute to addressing SDGs 4, 5, 7, 10, 13, 14 and 15 (**Table 1**; **Figure 2**).

The obvious benefit of well-functioning collections is the ability to (re-)examine fossil collections, drill cores or hard to obtain samples from remote areas. Nakrem et al. (2023), for instance, present the Arctic collections at the Natural History Museum at the University of Oslo, including fossil and rock samples from remote and currently politically unreachable areas such as Novaya Zemlya acquired over a century ago.

A secondary role of museums is outlined by Lanzinger and Garlandini (2019) who consider the changing role that all museums play in the context of the SDGs. From the traditional "*guardians of the past*," museums are increasingly tasked with presenting options for future and sustainable solutions (Lanzinger and Garlandini, 2019). In the context of geoscience-focused museums these may include both exhibits about the past climate variability and life evolution, but also considerations of climate change mitigation options in the future.

Geoheritage and Geotourism (SDG 4, 13, 14, 15)

Geoheritage is the geological aspect of natural and cultural heritage, and directly links to SDGs 4, 13, 14 and 15 (**Table 1**; **Figure 2**).

Geoheritage sites comprise geological features with significant global relevance. Gordon (2019) reviews some of the underlying principles of geoconservation, both in terms of single geoheritage sites and in terms of protecting larger areas. The UNESCO Global Geoparks, established from 2000 onwards, holistically manage such features through conservation, education, and sustainable development. UNESCO Global Geoparks are already well suited to promoting geoscience education for sustainability in schools (Catana and Brilha, 2020). Specific examples are available for, for instance, the Lanzarote and Chinijo Islands geopark (Martínez-Frías et al., 2017). A new working group in the Global Geoparks Network on the SDGs will cement this in the future.

Another aspect is the heritage inherent in data collected by geoscientists, notably physical material. As outlined above, natural history museums often have large collections of fossils and rock samples (e.g., Nakrem et al., 2023). Drill cores, on the other hand, are usually stored in dedicated core repositories. In the United States of America (USA) alone there are about 50 such repositories (Arends et al., 2021). The global drill core record represents an excellent opportunity to constrain past climate perturbations, provided that drill cores are curated, archived and made available to the scientific community (Planavsky et al., 2020). Unfortunately, these efforts are often costly (though minimal compared to the initial data acquisition costs), and for instance the entire USA Antarctica marine core database recently needed to be relocated (Witze, 2016).

Higher Education and Research

Research and higher education are central to many SDGs through both educating the next-generation of multi-disciplinary "sustainability" experts and conducting targeted research to help society reach the SDG targets.

Geoscience Research (SDG 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17)

Geoscience research can contribute to all SDGs. The key is to integrate geoscientific competence in SDG-related research, working across and with other disciplines, notably the social sciences. Scown (2020) notes that while research on the SDGs has exponentially increased from 2015, only a small fraction of these is related to geoscience. The Earth System is complex and requires policymakers to think longer term and across scales (Scown, 2020), both of which are natural traits for geoscientists.

Geoscience Teaching (SDG 1, 4, 5, 13)

Teaching (geosciences) contributes to SDGs 1, 4, 5 and 13 (**Table 1**; **Figure 2**).

Avelar et al. (2019) reviews literature on how education in general, albeit with only one article focusing on geoscience education (Jessell et al., 2018), links to the SDGs. Annan-Diab and Molinari (2017) argue that interdisciplinarity is the key in implementing SDGs in education, ideally with insights from both the public and private sectors. The breadth and interconnectedness of the SDGs make inter-connected education crucial, both for graduates but also for professionals. This applies especially to managers who can make a difference in aligning company strategies with the SDGs (Annan-Diab and Molinari, 2017).

On the positive side, many universities already offer inter-connected courses focusing on sustainability, or link existing courses more directly to specific SDGs. Pálsdóttir and Jóhannsdóttir (2021), for instance, provide an overview of how the SDGs were implemented at the University of Iceland. Almazroa et al. (2022) reviews how SDGs are implemented in teacher-education program at higher education institutes.

The ongoing digital revolution in the geosciences also opens possibilities for alternative education and outreach. Zapata-Paulini et al. (2023), for instance, present a mobile-based augmented reality application to present glacial retreat in the Peruvian Andes to a wider audience.

The use of digital outcrop models, photospheres and thematic geoscientific data integration further facilitates education. Virtual field trips have opened up geoscience fieldwork to a much broader audience (Mead et al., 2019; Whitmeyer et al., 2020). The uptake of virtual field trips has been accelerated due to the COVID-19 pandemic (Whitmeyer and Dordevic, 2020; Pugsley et al., 2022). In the High Arctic, the University Centre in Svalbard has been actively using such digital tools, notably digital outcrop models and drone-based photospheres, to supplement its field-based education since 2016 (Senger et al., 2021; Horota et al., 2022b; Betlem et al., 2023; Horota et al., 2024).

Data and Skill Sets

Reaching the SDG targets will require geoscientists to adapt other skills than they are traditionally used to. Specifically, adopting geophysical tools, technologies and workflows developed by the petroleum and mining industries is crucial to reach many SDGs. Similarly, (geospatial) data science can help geoscientists to analyze the huge amount of data and translate it into key maps or products of direct relevance for stakeholders and decision makers.

Geophysics (SDG 6, 9, 11)

The broad discipline of geophysics links to all SDGs, but specifically contributes to SDGs 6, 9 and 11.

Capello et al. (2021) map geophysical applications and practices to all the SDGs. Furthermore, they present concrete geophysics-enabled targets and present collaboration and expansion opportunities for geophysicists for each SDG. For SDG9 (Industry, innovation, and infrastructure), for instance, focus is on using geophysics to construct and monitor smart sustainable cities and critical infrastructure. Listed geophysical enablers for further expansion opportunities include, amongst others, drones for geophysical mapping, subsurface characterization and large-scale inSAR data access.

Clearly, geophysicists have a crucial role to play in many of the geoscience professions outlined here. Interestingly, many of the geophysical methods, workflows and software that were initially developed for exploration for petroleum or minerals have a strong role to play in monitoring climate change (for instance passive seismic methods for monitoring thawing permafrost; Cheng et al., 2022; Stemland et al., 2021) and contributing to the SDGs by characterizing the near-surface sediments that are crucial in urban infrastructure.

GIS and Remote Sensing (SDG 1, 9, 13, 14, 15)

Geographic information systems (GIS) and remote sensing in general have strong links to many SDGs, most concretely to SDGs 1, 9, 13, 14 and 15.

Pirasteh et al. (2019), for instance, propose a method for automatically extracting the extent of buildings from LiDAR and drone-based photographs. In essence, the work illustrates the necessity of translating the immense amount of information gathered from global to local scale to knowledge of direct relevance for the society.

One such example is presented by Dehls et al. (2019) at a country scale, Norway, by presenting inSAR data on an easy-to-use web-based interface illuminating areas of subsidence and uplift. Time-series data can be easily extracted from any part of Norway and the resource managed by the Geological Survey of Norway is invaluable for instance in large-scale constructions and monitoring and characterization of geohazards.

Satellite data with global coverage also of areas with limited or no *in situ* monitoring systems has strong potential for contributing to sustainable development. Sheffield et al. (2018) review water resource management options from satellites, including derivation of key parameters such as soil moisture, groundwater presence and quality and surface water levels. A key take-home message is that often complex satellite-derived data sets need to be "translated" to knowledge parameters with direct societal impact.

Estoque (2020) reviews the links between remote sensing and the SDGs—noting amongst others that 18% of the SDG indicators can be directly or indirectly tested by existing remote sensing data.

Data Science and Analytics (SDG 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17)

The ongoing revolution in data science and analytics is already making a large impact on the geosciences and will contribute to most of the SDGs.

The explosion of global scale earth observation (EO) data goes in-parallel with the advanced usage of (semi-) automatizing data analysis through for instance machine learning (ML). In essence, geoscientists need to rethink how the immense "big data" datasets will need to be analyzed to solve challenges related to the SDGs (Guo et al., 2020). In this aspect, the International Union of Geological Sciences (IUGS) "Big Science Program" is an important milestone, recognizing that geosciences need not just to acquire a lot of new data but also consider how these data are analyzed and "translated" into useful knowledge and products for society. Cheng et al. (2020) reviews numerous examples of studies utilizing the emerging integrated techniques (**Figure 14A**), and provides perspectives for the future. One concrete example of such a project is the IUGS-affiliated Deep-Time Digital Earth program that amongst others aims to harmonize global data about Earth evolution and make it FAIRly available through tailored services (Wang et al., 2021).

With respect to data availability, EO data include high-frequency (often daily), high-resolution satellite imagery (e.g., from planet.net), EO data cubes (**Figure 14B**; Sudmanns et al., 2023) and various other data products. Numerous case studies are published on the use of EO data in supporting the SDGs, with Aggarwal et al. (2020) for example, investigating the hydrological cycle of North West Himalaya using EO data and hydrological modelling.

Workflows are evolving continuously. Google Earth Engine, the data analysis framework that revolutionized EO analysis in many scientific fields, was launched in 2010 and continues to be an important tool in many geoscientific fields (e.g., Kumar and Mutanga, 2018; Tamiminia et al., 2020). The inclusion of machine learning algorithms in geoscientific applications is facilitating addressing the immense data quantities that are being generated (Lary et al., 2016).

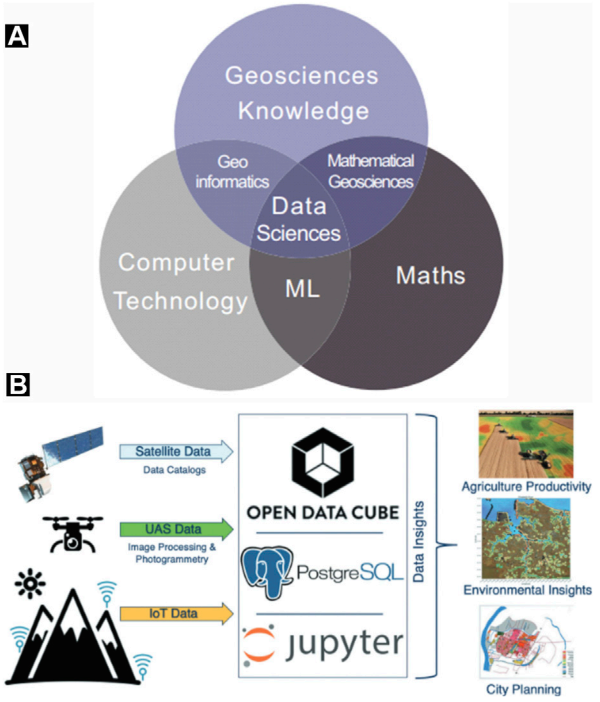

FIGURE 14 | (A) Data science at the intersection of mathematics, computer technology and geosciences. Reproduced from Cheng et al. (2020), licensed under CC BY 4.0. **(B)** Integration of various data types, data analysis contents and data products. Reproduced from Sudmanns et al. (2023), licensed under CC BY 4.0.

Innovation and Frontier Exploration

Geoscientists do not only cover the terrestrial surface of the Earth, but also investigate the oceans and other planets.

Oceanography (SDG 13, 14)

Oceans cover 71% of the Earth's area and oceanography is directly linked to SDGs 13 and 14.

von Schuckmann et al. (2020) reviews ocean science and management within the context of the SDGs, covering both the environment, societal and economic relevance. Ryabinin et al. (2019) outlines the UN's decade on ocean science.

Within oceanography, geoscientists are primarily involved in understanding present and past oceanic circulation, with direct implications on the climate. Deciphering the Eocene-Oligocene opening of the Fram Strait, the only deep-water connection from the Arctic Ocean and a major driver in the global oceanic conveyor belt, is an excellent example. Studies include investigations on the tectonic drivers (e.g., Engen et al., 2008), paleobathymetry (e.g., Straume et al., 2022) and climatic proxies (e.g., Werner et al., 2016).

In recent years, the exploration for critical minerals such as manganese nodules, massive seafloor sulphides and cobaltrich crusts on the seabed has increased. Norway, for instance, has in 2024 opened up its part of its Exclusive Economic Zone up for exploration and development, though a holistic approach will be needed to manage such resource extraction most sustainably (Ellefmo et al., 2023).

Planetary Geology (SDG 9)

Planetary geology has emerged as a multidisciplinary discipline since the Space Age, utilizing geological methods to understand other planets beyond earth. In terms of SDGs, planetary geology is directly linked to SDG9.

The evolution of geology from an Earth-centered discipline to also concern other planets is well described by Marvin Ursula (2002). Most of the work is concerned with analyses of extraterrestrial material collected by astronauts, unmanned missions or as meteorites. Schultz et al. (2010) reviews the datasets available for structural geology studies of other planets, highlighting that the remote sensing in many cases exceeds the resolution of Earth-based products. Naß and Gasselt (2014) call for increased data collaboration and standardisation of geological mapping of other planets (notably Mars and the Moon), in the context of ever-evolving geological maps of other planets.

With respect to the SDGs, planetary research drives innovation through targeted efforts that push the limits of both scientific discovery and technological advances. One excellent example is the series of Arctic Mars Analog Svalbard Expeditions (AMASE; Stern et al., 2013) where astronauts, engineers and scientists worked for a decade in the remote Svalbard environment to develop the hardware and workflows to make scientific missions to Mars possible. Furthermore, some of Earth's environments are protected as geoparks primarily for their connections to other plants, such as the volcanic Geopark at Lanzarote often utilized by space missions (Martínez-Frías et al., 2017).

Finally, the exponential emergence private actors on the space market in recent years is a double-sided coin. On the one hand, the space data provided by low-orbit satellites is, as discussed above, extremely useful in addressing many of the SDGs. On the other hand, the spacecraft production and orbital launches have a large environmental footprint, prompting Wilson and Vasile (2023) to describe the space sustainability paradox.

Social Geology/Human-Environment Interaction

Mata-Perello et al. (2012) define social geology as "the discipline of geology that studies the interaction among the geological environment and the social development." While all SDGs are directly or indirectly bridging this gap, it is the interface between sociology and geology where this interaction is most apparent.

Non-Governmental Organisations (SDG 1, 3, 6, 9, 14, 15, 16, 17)

Many geoscientists work in NGOs, who are linked to SDGs 1, 3, 6, 9, 14, 15, 16 and 17.

Wagaba et al. (2023) provide a case study of small NGOs working on water-related projects in eastern Africa who require access to geological data for their work. In many cases, however, bureaucratic obstacles to obtaining free government geological data, inappropriate data format, and limited funding from donors to obtain such data and the relevant expertise all complicate their important work (Wagaba et al., 2023).

Many NGOs are funded by the developed world and operate in the developing world. Appropriate geoscientific applications with relevant expertise can support many NGOs. However, Petterson (2019) also highlights some key barriers between geoscience organizations and development agencies, including differing world views, performance rewards and values. Petterson (2019) present how the British Geological Survey contributed geoscientific expertise to both the Salomon Islands and Afghanistan, before concluding that an interconnected geoscience ethos approach is desired for the way forward.

Science Policy (SDG 1, 3, 6, 9, 14, 15, 16, 17)

SDG17 is all about global partnerships. In this context, we should investigate if existing international frameworks, commissions, networks, and systems (**Figure 15**) are functioning as required to achieve the SDGs or if adjustments are necessary. The big dilemma is, unsurprisingly, the interaction between these various bodies, with sometimes conflicting agendas.

Agrogeology (SDG 1, 2, 3, 6, 14, 15)

Agrogeology is the study of minerals for agriculture—or, as put forward by (Straaten, 2007), "the use of rocks for crops." Consequently, Agrogeology is directly linked to SDGs 1, 2, 3, 6, 14 and 15.

Soils are obviously a crucial element for agricultural production, but also have global roles to play as a major carbon pool with climate implications, a source of raw material, defining biodiversity and an archive of geological and archaeological heritage. Smith et al. (2021) reviews how soils impact the various SDGs while (Pratt et al., 2020) review the interlinkages of the geosphere with agricultural production.

Agrogeology is specifically concerned with the influence of bedrock materials on soil fertility. Van Straaten (2017) reviews the evolution of Agrogeology as a science from the First International Agrogeological Congress in Budapest in 1909 (Unger and Brezsnyánszky, 2010), through numerous name changes, to present day case studies on multiple continents. These include, amongst others, regional geochemical surveys of soil fertility in China's Jiangsu Province (Liao et al., 2007) and a major agrogeological project to increase farmer's yields using locally sourced geological resources (Chesworth et al., 1989).

The Rochagem movement started in Brazil as early as the 1950s to use crushed rocks to naturally re-mineralize soils and increase agricultural production (Manning and

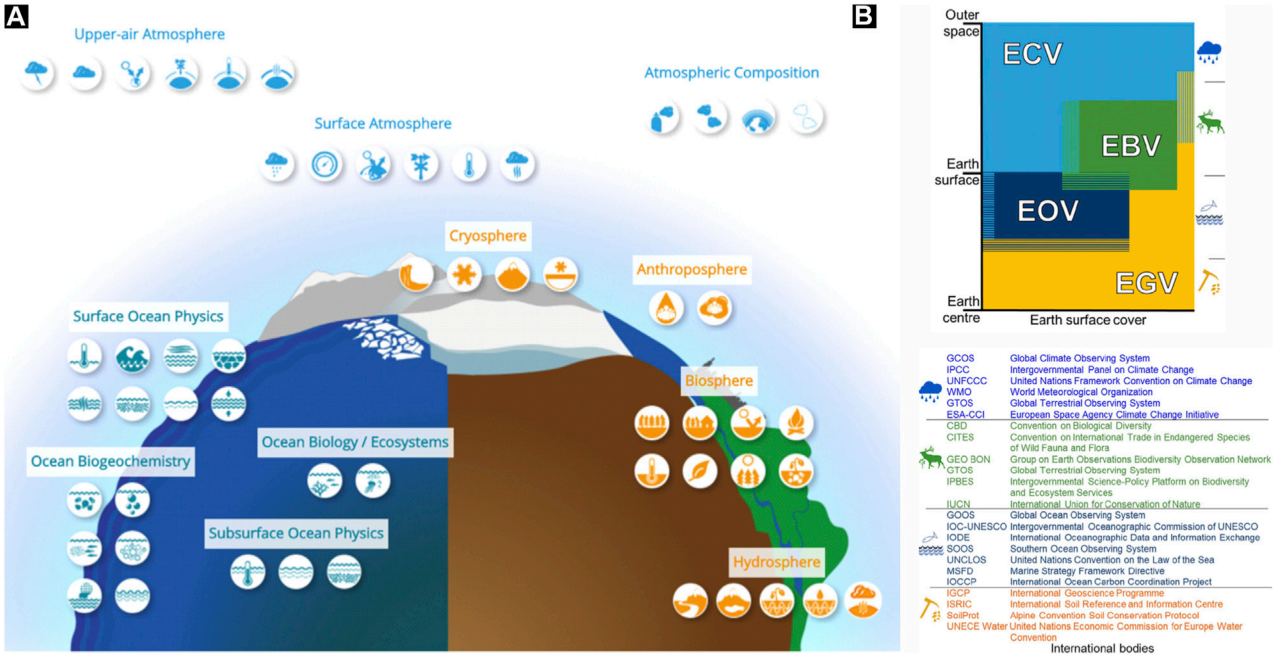

FIGURE 15 | (A) Schematic cartoon of the essential climate variables, Reproduced from NASA. **(B)** Overview of key international bodies in the framework of essential variables (EVs), in the climate (ECV), biosphere (EBV), oceans (EOV) and the geosphere (EGV). Figure from Schrodt et al. (2019). Reproduced from PNAS with permission.

Theodoro, 2020). The dramatic increase in the cost of fertilizers in the early 21st century led to a more systematic focus on "Rocks for Crops," starting with an international conference in Brasilia in 2004 (Manning and Theodoro, 2020). The movement subsequently gained international traction and site-specific studies are now available from many parts of the world, for instance Malawi (Chiwona et al., 2020). Ciceri and Allanore (2019) review, in the context of the whole of Africa, how fertilizers are used and how local fertilizers can help achieve food self-sufficiency.

Kritikakis et al. (2022) examines a 182 km^2 large study area in northwestern Crete with important agricultural production (olives, avocado and citrus crops) using both soil geochemical and hydrogeological data, locally supplemented by near-surface geophysical techniques. The integrated approach incorporating geological and geophysical mapping with soil sciences in a GIS-environment is a solid role model for other studies.

Medical Geology (SDG 3 and 6)

Medical geology is a relatively new research field that links geogenic contaminants to human populations, and is linked to SDGs 3 and 6 (**Table 1**; **Figure 2**).

Bundschuh et al. (2017) introduce the term medical geology and link it to the SDGs. Like Agrogeology, medical geology concerns how the underlying geology controls surface conditions, though in this case concerning how geogenic contaminants from rocks and minerals influence the environment and humans. Geogenic contaminants affect the many environments (i.e., hydrosphere, pedosphere and atmosphere) and may expose humans directly or through water, crops, livestock or fisheries (Bundschuh et al., 2017).

Case studies are available from many sources and contaminants, including arsenic in Latin America (Bundschuh et al., 2021), fluoride concentration in Tanzania (Ijumulana et al., 2020) and arsenic and fluoride globally with specific focus on India (Jha and Tripathi, 2021). In all cases, geoscientific expertise is crucial to understand the origin, contamination pathways and remediation strategies.

FUTURE DEVELOPMENTS

I have so far investigated how various geoscientific professions relate to the SDGs. However, even since the start of the SDGs in 2015 there have been significant advances that influence progression to the identified SDG targets by 2030.

Big Data, Artificial Intelligence, Data Analytics and Data Availability

The exponential increase in data amount and availability through big data is already changing how SDG indicators are monitored, and targets reached. The UN recognized the possibility of leveraging big data early on, establishing the UN Global Pulse in 2009 as an innovation hub for reaching the SDG targets. Hassani et al. (2021) investigate first-order Google-search trends of big data compared to the 17 SDGs, providing specific examples of how big data may contribute to the SDG trends.

There are numerous recent contributions that link big data analysis, especially with earth observation (EO) data, to SDGs (Guo, 2017; Zhou et al., 2021; Guo et al., 2022). The key is to focus on extracting information, not data, from these immense data sets. As an example, provision of usable GIS data on cadastral boundaries can significantly influence SDG1 (no poverty) but needs to be usable by the local communities. Similarly, crisis management following geohazards like flooding using high-resolution satellite images or UAVs must be specifically tailored to the needs (knowledge type, spatial and temporal resolution, etc.) of the local disaster managers (Antoine et al., 2020; Zwęgliński, 2020).

The same applies to data science in general. Data should not only be openly provided, but integrated around four main pillars of science-product-stewardship and services (Wyborn et al., 2021). In this approach, the end user primarily uses the services to access the knowledge that is critical for their task, but has adequate information on the data limitations, a longer-term platform thanks to good curation and data products that are applicable to solving the problem at hand.

Energy Transition: A Call for Geoscientists

The energy transition is likely one of the largest challenges humankind has ever faced. The shift from fossil fuel driven primary energy supply to one dominated by renewables is technically feasible but requires extensive commitment, both socially and economically. In parallel, the decarbonization of the petroleum industry through initiatives such as CCS is ongoing. The key in this process is that geoscientists have the skill sets to contribute to renewables and low-carbon energy sources, with many of the subsurface skills used for decades in the petroleum industry forming an important foundation in subsurface interpretation needs during the energy transition. Furthermore, the fact that investors prefer to invest in non-fossil energy sources does not imply that the world does not need any fossil fuels anymore—on the contrary the increasing world population and raising living standards (and associated *per capita* energy demand) will require additional oil and gas production within the next decades globally.

Davies and Simmons (2020) ask themselves "*Who needs stratigraphers, sedimentologists & paleontologists*," highlighting a somewhat existential geoscience crisis and plummeting student recruitment numbers. However, by outlining the roles that geoscientists can play in the energy transition the authors conclude with the statement that "*stratigraphers, sedimentologists and paleontologists are the custodians and curators of Earth history, perfectly placed to advise on the future of the planet*" (Davies and Simmons, 2020).

Geoscientists can contribute to many sectors in addition to the oil and gas sector. An obvious contribution is to CO_2 storage and geothermal energy exploitation, but also seabed mapping and enhancing recovery in hydrocarbon fields are important contributions.

SUMMARY AND CONCLUSION

In this contribution I have reviewed how different geoscience disciplines contribute to UNs 17 Sustainable Development Goals.

I conclude that geoscientists significantly contribute to the SDG targets. Geoscientists are directly involved with mitigating geohazards, expected to increase due to climate change. Geoscientists also secure affordable energy to society, be it through the sustainable exploitation of fossil fuels that remain the most important primary source of energy, or by contributing to enhanced focus on renewable and low-carbon energies such as geothermal, hydropower or nuclear during the energy transition. Strong geoscientific involvement is also required in challenging geoengineering tasks, notably CCS, that must be, according to the IPCC, deployed at an exponential rate to reach global emission targets. The energy transition also requires a vast amount of materials, notably critical minerals, which geoscientists must find and sustainably produce to meet the rapidly rising demand.

In conclusion, the world—and geoscientists alike—face some of the biggest challenges in human history as exemplified by the motivation of establishing the SDGs to end global poverty and hunger, facilitate economic growth and social development and protect the environment by 2030. Society is on track to fulfill some of these, but many targets will unfortunately not be met. The geoscientific community must nonetheless work together with social scientists, engineers and local-national-global authorities to reach all of these targets by 2030 or soon thereafter. To end on a positive note, geoscientists have through their contributions to society over the past centuries shown that the skill sets they possess are crucial to meeting this challenge. Geoscientists will not save the world and tick of all the SDG targets alone—but with targeted co-operation with other disciplines, including social sciences and engineers, geoscientists can certainly contribute to reaching these targets.

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CONFLICT OF INTEREST

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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