New Prospects and Trends in Applied Geoscience

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From education, public perception to employment, research and funding, geoscience is facing serious challenges and is competing with many lucrative fields, such as bioscience, nanoscience, artificial intelligence, business management, and others. In order to grow geoscience and publicize its value, it is imperative to showcase the means and manners by which geoscientists serve the wellbeing of society. This article reports on the results of a survey on how several areas of applied geoscience will be critical in the coming years, and how geoscientists can seize on these opportunities to strengthen their science, profession, and community.

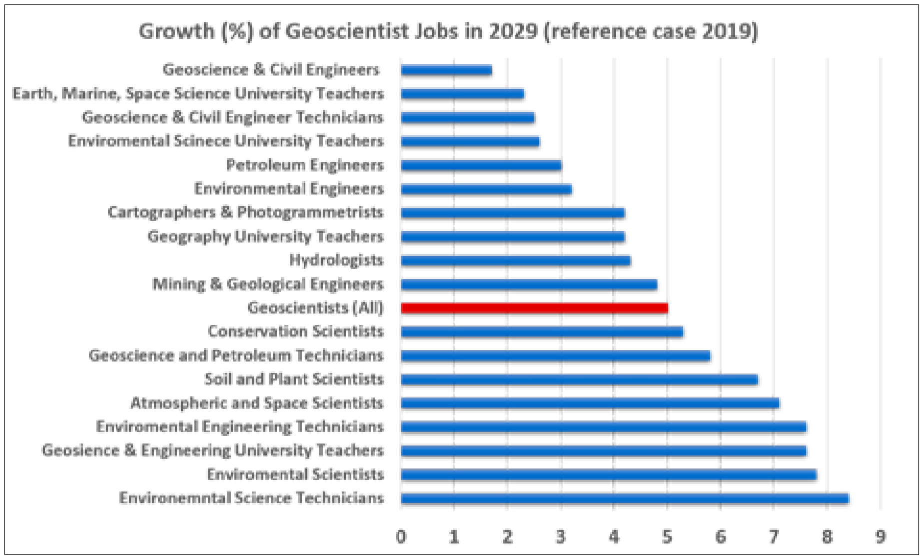


Figure 1 - Growth (in percentage) of geoscientist jobs from 2019 to 2029 according to the US Bureau of Labor Statistics (2020, AGI, 2020a).

Geoscience Education and Workforce

Most people including children are fascinated by minerals, fossils, and rocks, and are interested to know about the life of the dinosaurs, how mountains uplift, and other geological lore. Indeed, news about discoveries in earth science are popular (Sorkhabi, 2019). Ironically, however, Earth science is relatively underrated in our schools and K-12 education. A 2015 US survey found that only 22 states accepted an Earth and Space Science course for graduation, and only two states required a year-long Earth/Environmental Science course whereas the number of states for required Life Science and Physical Science courses for graduation were 50 and 30, respectively (Benbow and Hoover, 2015). Crisis in geoscience education is not limited to high schools. In recent years, college enrollments in geoscience programs in the US, UK, India, Japan, and probably many other countries have declined. According to Christopher Keane of the American Geosciences Institute (AG), geoscience majors in US universities decreased 21% from 31,744 in 2016 to 25,015 in 2019, and for the pandemic year of 2020 a drop of more than 10% was estimated (Saucier, 2020). Against this background, demand for geoscience jobs, according to the US Bureau of Labor Statistics, will increase by 5% from 460,242 in 2019 to 482,726 in 2029; most of these jobs will be in the environment, energy, and mineral resource sectors (Figure 1). Considering that 27% of the existing geoscientists will be retiring by 2029 and that new graduates entering workforce are projected to be 26,000, there will be about 130,000 deficits in geoscience jobs in 2029 (AGI, 2020a). Another estimate by Bartlett (2018) states that the US will need 14,000 new geoscientists in 2026 (compared to 2016).

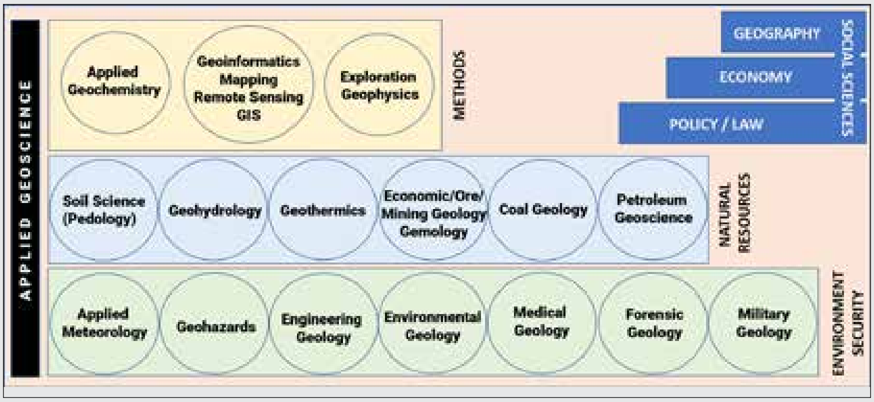
It is thus important to communicate the value of geoscience to the public, school boards, mass media, and policy makers. This is a crucial challenge for the geoscience community; it is also a task that geoscientists can best perform. We also need to portray a new image of the geologist beyond one who digs for fossil fuels and loves earthquake incidences.

With this background, in 2019-2020, I conducted a survey of the most important questions and issues in geoscience. The survey was emailed to hundreds of geoscientists and circulated via community posts on the websites and email newsletters of Geological Society of America (GSA), American Geophysical Union (AGU), and American Institute of Professional Geologists (AIPG). A total of 136 scientists (75% from the USA) responded. Even though 75% of the survey respondents were from the academia, they still emphasized that several areas of applied geoscience (see Box 1 on page 57) will play significant roles in bringing direct benefits to society. The following topics were suggested by seven or more respondents as critical areas of research and development (Table 1).

Global Warming

Nearly 30% of the respondents suggested global warming as the most critical issue of our time. The complex issue involves many areas of research including in-depth understanding of climate change and carbon budget and cycle (sources and drivers as well as sinks and feedbacks), better forecasts and modeling of the impact of global warming on the environment

Box 1 - What's in a Name: Applied Geoscience



Geology is traditionally divided into three groups of disciplines: Physical geology (studies of Earth's materials and processes studied by mineralogy, petrology, geomorphology, and structural geology/tectonics); historical geology (stratigraphy and paleontology); and applied geology, which AGI's *Glossary of Geology* defines as "the application of various fields of geology to economic, engineering, water-supply, or environmental problems." Since there are methodological connections between geology, geochemistry and geophysics, it is better to group applied geology with applied geochemistry and applied (exploration geophysics) under the term "applied geoscience." Various disciplines of this broad field are shown in the above figure. Certain social sciences also contribute to applied geoscience. Related terms previously used include the titles of *Applied Earth Science* by Daniel Turner (1969) and *Geology and Man: An Introduction to Applied Earth Science* by Janet Watson (1983).

Table 1

This Survey (total 136 geoscientists)	AGI (2020) Report
Global Warming (40)	Climate Change
Petroleum Industry and Geoscience (39)	Water
Mineral Resources (16)	Energy
Education and Workforce (15)	Natural Hazards
Natural Hazards (12)	Soils
Water Resources (11)	Mineral Resources
Energy Resources (10)	Oceans & Coasts
Environmental Geology (7)	Waste Disposal
	Workforce

Table 1 - Priority fields in applied geoscience: This survey and critical needs were suggested by the American Geoscience Institute (AGI, 2020b).

and societies, and more importantly working out technological and policy procedures to reduce the atmospheric greenhouse gases, especially carbon dioxide and methane emissions from fossil fuels.

The Petroleum Industry and Geoscience

Similarly, about 30% of the respondents considered that the future of the petroleum industry and petroleum geoscience and engineering is paved with concerns and challenges.

Since the 1860s, the petroleum industry has increasingly shaped the modern world; oil and gas have provided abundant and affordable supplies for lighting, heating, and transportation on land, the sea, and in the air, in addition to myriad petrochemicals and medicines. Since the 1910s, the petroleum industry has been closely associated with many universities. A large number of geology and petroleum engineering departments were founded in universities close to petroleum basins such as those in Texas and Louisiana. The industry has traditionally hired a large number of geology, geophysics, and engineering graduates, and has funded numerous research consortia and graduate theses, aside from the research laboratories and institutes that major oil companies operated themselves. Indeed, certain fields in geoscience, such as basin analysis, micropaleontology, sequence stratigraphy, organic geochemistry, subsurface imaging, petrophysics, well logging, and seismic and other geophysical surveys, were spearheaded and financed by the petroleum industry. Without these contributions, our knowledge of subsurface geology and stratigraphic record would have been limited to bedrock outcrops which cover only 34% of the Earth's land surface. Given this history, oil market crashes adversely affect geoscience departments, education, and research. For instance, following the oil market crash of 2014 undergraduate enrollments in geoscience programs in the USA fell by 5% for the 2015-2016 academic year (Keane, 2017). The 2020 oil crisis due to the Covid-19 pandemic has also caused serious concerns (Sorkhabi, 2020). The petroleum companies and oilfield service companies have cut back on expenditures and have laid off a large portion of their workforce, particularly geoscientists. Given the worldwide movements to combat the global warming the future growth of the petroleum industry is not clear: Will the industry evolve and reinvent itself, or will it give way to other energy, mineral and environmental industries; and if the latter, will these industries be geoscience-intensive and highly supportive of research and education? These questions currently facing the geoscience community are at the heart of discussions on how to reform and develop geoscience education programs and research fields (Simmons et al., 2020).

In order for the petroleum industry to re-invent itself, it has to address two critical areas – environmental sustainability, and reducing exploration and production (E&P) costs per barrel of oil. Science and technology will play key roles in achieving these targets.

To be environment friendly and reduce its carbon footprint, the oil and gas industry has to invest in the science and technology of carbon capture, utilization and storage (CCUS), which currently plays a minimal role in the industry. As of 2019, there were only 17 operating CCUS plants in the world, capturing 31.5 million tons of carbon dioxide annually (Fajardy et al., 2019); most of these were industrial not power plants (Element Energy, 2018).

In the past decade the shale oil revolution in the USA has doubled the country's oil and gas production. Nevertheless, the shale drilling and production technologies are far from perfect, and the shale revolution is still limited to a few basins in the USA. Some of the challenges facing the shale oil industry include:

- Avoiding gas flares in shale oil fields (and instead utilizing this natural gas resource)
- Reducing water consumption for hydraulic fracturing (or even adopting dry gas for fracking)
- Reducing methane emissions from the operating fields
- Control and mitigation of induced seismicity
- Optimization of well placement
- Treatment and reuse of produced formation waters
- Characterization and modeling of porosity and permeability types in mudrock/shale reservoirs
- Developing well logging technologies specific for mudrock/shale formations
- Shale structural geology and fracture mapping and analysis
- Modeling and calibration of hydrocarbon generation-migration-accumulation systems in shales
- Quantification of generated, migrated or residual hydrocarbons in shale plays.

To reduce its E&P costs and increase it profit margin, the petroleum industry must adopt smarter and more efficient methods. Some of the suggestions in this regard made by the survey participants include:

- Smart databases incorporating the 150-year legacy data in new digital formats
- Applications of machine learning and artificial intelligence to petroleum data analysis and interpretation
- Integrating petroleum geoscience and engineering in the industry's workflows
- 4D modeling and improved subsurface mapping and imaging
- Improved recovery factors of oil and gas from reservoir formations

Energy Resources

Closely associated with the state of the petroleum industry is the energy transition. The world (as well as the geoscience community) is facing a huge dilemma. On the one hand, the catastrophic threat of global warming (mainly from the burning of fossil fuels) is an urgent call to move toward energy sources with the least carbon footprints. On the other hand, coal, oil and natural gas still account for 85% of the world's energy supplies, and a rapid transition to replace these energy-dense fossil fuels will pose formidable political, economic, and technological challenges. Added to this dilemma is the fact that global energy demand will grow (not decline) in the coming decades as the flow of abundant, affordable and dependable energy is critical to life standards of the developed world and development of low-income nations. These trends provide geoscientists with both challenges and opportunities in exploring and developing energy resources. For developing renewable energy sources and massive electrification of transportation to replace oil, exploration and production of energy minerals (such as rare earth metals for wind turbines and lithium and cobalt for batteries) will be crucial.

The energy scenario in the coming decades will be a mix-energy market (Figure 2), in which several resources and industries will compete for investments and profits as well as sustainability and social license to operate (SLO) (Figure 3).

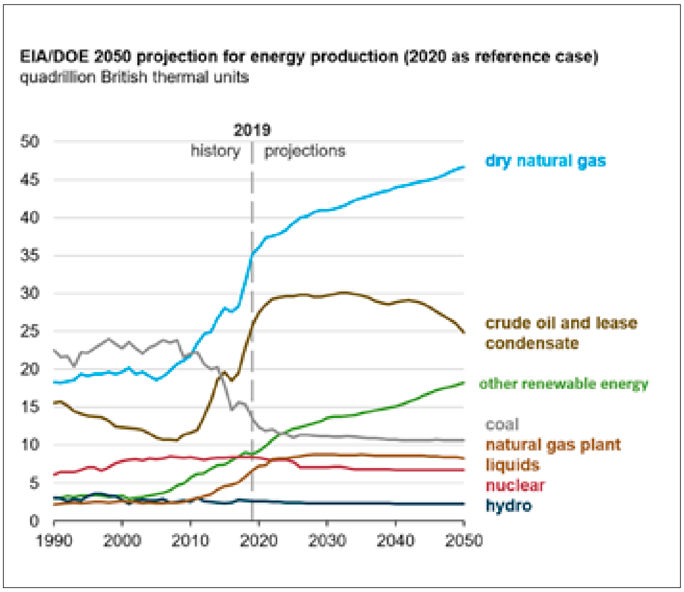


Figure 2 - 2050 projection of energy production by sources (EIA/DOE, 2020)

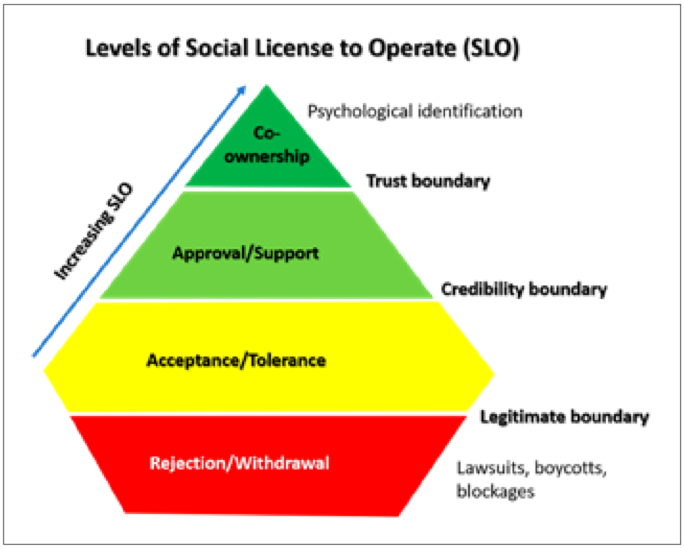


Figure 3 - Various levels of Social License to Operate (SLO) for companies, as a measure of their social accountability, acceptability, and support (modified from Thomson and Boutilier, 2011)

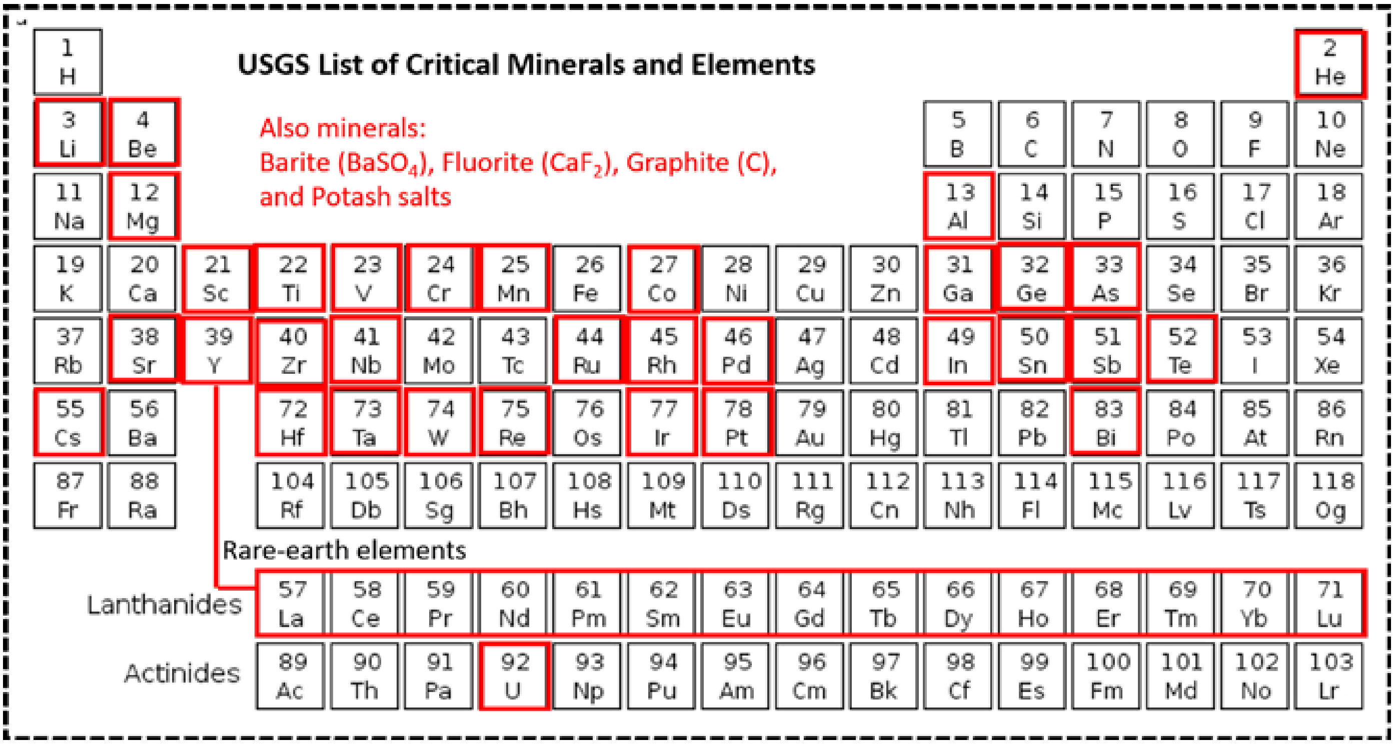


Figure 4 - List of critical (strategic) minerals identified by the US Geological Survey (Frontier et al., 2018) depicted on the periodic table of elements. If you do not know or remember all of these symbols for the elements, you are not alone (the author of this article belongs to your group), but as geologists, it is better to be familiar with critical minerals.

Mineral Resources

Everyday life and modern industries all depend on a vast number of minerals and elements extracted from Earth. Mineral exploration has always been at the heart of geoscience but the field is expected to grow as global demand for minerals will increase and critical (strategic) minerals will dominate national security and geopolitics. The US Bureau of Labor Statistics (2020) forecasts that that while geoscientist jobs for oil and gas extraction may shrink by 13% between 2019-2029, workforce demand for mineral industries will increase by 32% for that period (AGI, 2020b). The US Geological Survey has published a list of critical minerals and elements (Figure 4) that require domestic exploration and production in order to reduce the country's dependency on foreign sources. The respondents in this survey envisioned that improved knowledge of reserve estimates, geographic distributions, geological concentrations, and industrial recovery (and environmental impacts) of critical minerals and elements will be important tasks for geoscientists.

Natural Hazards

Natural hazards are normal geologic processes; however, their tragic impacts on human life, structures and properties have increased due to population growth and concentration in megacities prone to natural hazards as well as unpreparedness especially in developing countries. Natural hazards include a diverse set of events resulting from tectonic, hydrological, meteorological, and climatic processes (Table 2), and many of them are inter-related, such as offshore earthquake-tsunami coupling. Large populations and settlements are located close to the tectonic plate boundaries with records of big earthquakes and explosive volcanoes (Figure 5). Earthquake geologist Robert Yeats has called megacities like Tokyo, Manila, Tehran, Istanbul, San Francisco, Los Angeles, Mexico City, Santiago, Lima, and several others as cities sitting on "earthquake time bombs" (Yeats, 2015).

According to the World Health Organization, in the 20th century, more than 10 million people were killed as a direct result of natural hazards, including floods (6.8 million), earthquakes (1.8 million) and hurricanes or tropical cyclones (1.1 million) (Bryant, 2005). During 2000-2019, more than 7,000 geophysical disasters killed approximately1.23 million worldwide (CRED, 2020). Natural disasters, especially those affecting megacities and infrastructures, indeed disrupt the world economy. Geoscientists and engineers can greatly contribute to studies of pre-

Table 2

Hazard Category	Hazard Types
Geophysical	Earthquakes; Mass movement (dry); Volcanic activity
Meteorological	Extreme temperature; Fog; Storm
Hydrological	Flood; Landslide; Wave action
Climatological	Drought; Glacial lake outburst; Wildfire
Biological	Epidemic; Insect infestation; Animal accidents
Extraterrestrial	Impacts; Space weather hazards

Table 2 - Classification of hazards according to the Centre for Research on the Epidemiology of Disasters (CRED), Brussels, Belgium

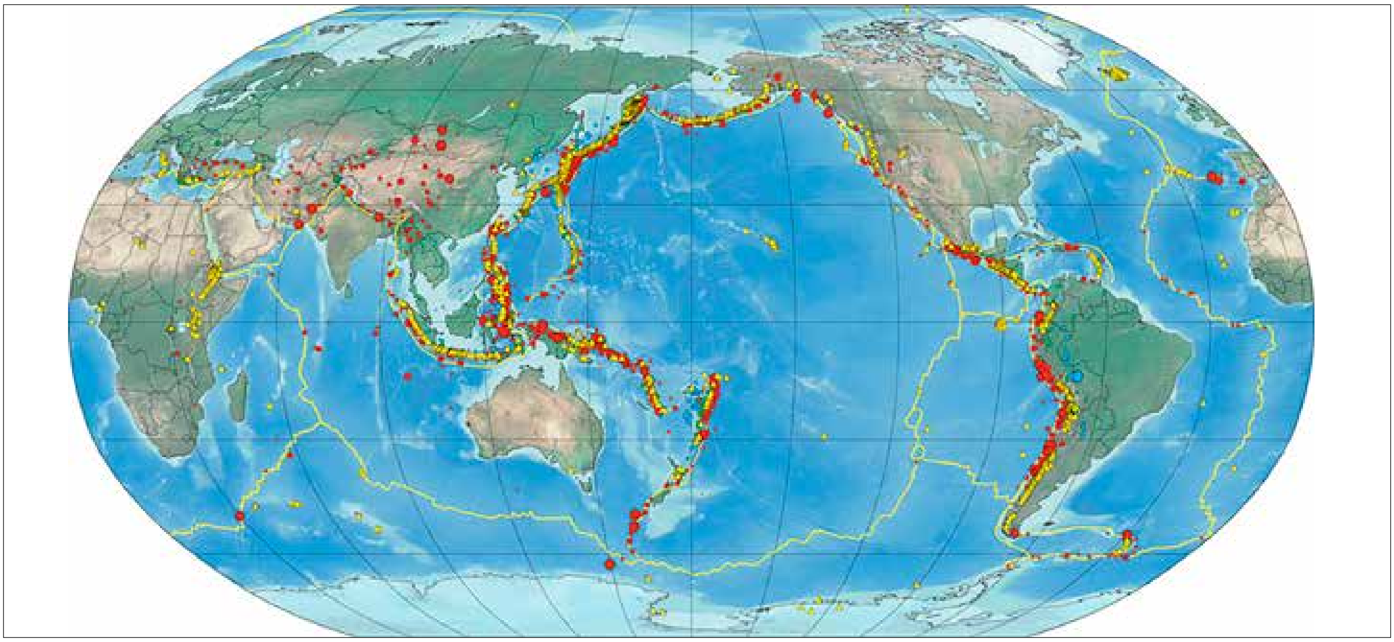


Figure 5 - Global seismicity with earthquakes larger than magnitude 6 for the period 1900-2012. Many megacities are located close to active plate boundaries. (Source: USGS)

cise mechanisms of natural hazards, risk assessments and mapping, warning systems, mitigation, and construction of hazard-resistant structures.

Water Resources

Underground and surface freshwater resources used for drinking, irrigation and other residential or industrial needs constitute only one percent of the global water budget (Figure 6). Although water is a renewable resource, freshwater resources are unevenly distributed both seasonally and spatially, depending on terrain and climate. Geoscientists and engineers will play an important role in detailed studies of the hydrological cycle and water budget, underground reservoir mapping and characterization, drilling and extraction of groundwater, water resource management especially in arid environments, optimal practices of watershed modification, desalination projects, and so forth.

Environmental Geology

Despite the obvious relationships between environmental quality and human health, rapid industrialization of the world has created environmental pollutants of various types. Humans are now a geological force impacting every part of the planet from the atmosphere and the oceans to mountains and forests. In 2000, atmospheric scientist Paul Crutzen popularized the term "Anthropocene" for the influence of human activities on Earth. The term became widely and informally used, and some geoscientists consider 1950 as the beginning of the Anthropocene Age because it marked the accelerating trend of atomic age, space age, population growth, petroleum consumption, atmospheric carbon dioxide increase, telecommunication, international tourism, motor vehicles, and other human-caused factors (Zalaseiwics et al., 2018; Ellis, 2018). Global warming, urban air pollution, acid rains, loss of biodiversity due to destruction of forests (with species that will never come back), desertification, nuclear and toxic wastes, plastic pollution of the oceans, silent erosion of top soil (that will take centuries to recover) and so forth are tragic records of the Anthropocene. Our failure to maintain the Biosphere 2 experiment (Nelson, 2018) demonstrates how precious and irreplaceable the Earth's biosphere is, and one which we cannot afford to fail. Environmental geology is thus a great contribution of geoscientists to society, and the significance of this field and the workforce needed for its multitude tasks are expected to rise in the coming decades.

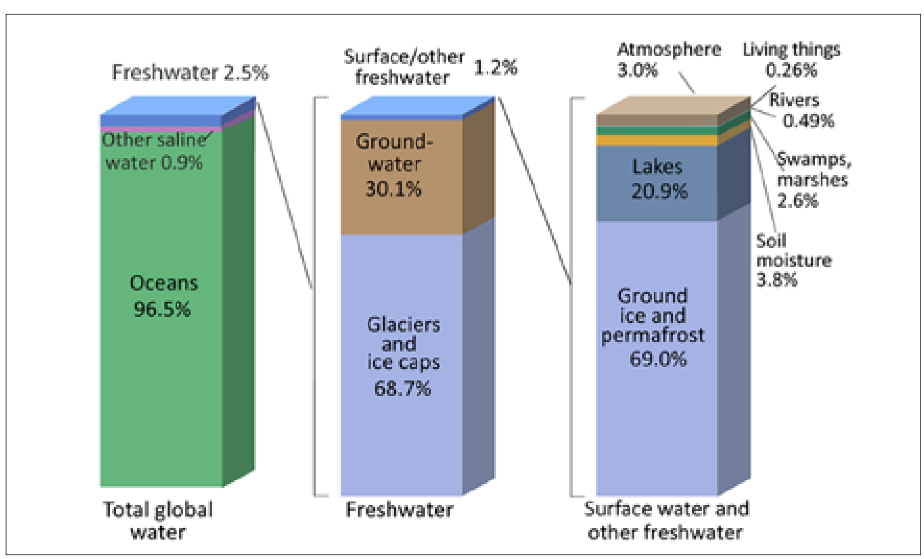


Figure 6 - Where is Earth's water? Water, water, everywhere but liquid freshwater is like a drop in the bucket (after Shiklomanov, 1993).

Applied Geoscience Comes of Age

It is important to study the interplay of geologic forces shaping and constraining civilizations on the one hand; and human use of resources and alteration of the environment, on the other hand. It is indeed possible to write the history and cultural development of humans in terms of their use of resources; from stones, water, soil, fire to metals, coal, petroleum, uranium and so on. At the same time, human populations and technologies have increasingly placed pressures on the environment and resources, and some scientists warn that, if these pressures continue relentlessly, the impacts will go beyond the carrying capacities of geo-environments. Applied geoscience will increasingly be useful in addressing the resource and energy needs as well as contributing to sustainable development and environmental protection.

The results of this survey are consistent with an AGI report (2020a) on a 9-point critical needs in geoscience research and development (Table 1), thus strengthening the importance of these trends and prospects in applied geoscience.

Acknowledgements

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